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ABSTRACT

The variation of resonant time duration with latitude, altitude, and f_N/f_H has been determined for the plasma resonances observed by Alouette I and Alouette II at the electron plasma frequency f_N, the electron cyclotron frequency f_H, the upper hybrid frequency f_T, and the harmonics nf_H where $n = 1, 2, 3, \cdots$. The duration of the f_N resonance was found to be critically dependent on the transmitted power; long duration f_N resonances (which are required in order to make electron temperature measurements based on the oblique echo theory for this resonance) can be excited with a transmitted sounder power as low as approximately 0.5 w. The f_H resonance has great potential as a diagnostic tool in a very rare plasma since under these conditions it has the longest time duration of any of the nf_H resonances; in a dense plasma, on the other hand, it is one of the weakest resonances observed. The $2f_H$ resonance is the only nf_H resonance that does not show a definite dependence of duration on latitude and the only one that shows a strong dependence on f_N/f_H; the other nf_H resonances show a definite dependence on altitude (as well as latitude). The resonances at $3f_H$ and $4f_H$ are observed strongest at high altitudes whereas the high order harmonics are consistently observed only at low altitudes. The nf_H observations with $n > 5$ indicate a stationary resonant region, extending only about 2 meters from the antenna, that is observed during its full time decay

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period (up to a few msec) in low latitudes; the observations are limited in high latitudes by the motion of the satellite. The results show that neither the theory based on longitudinal plasma waves of low group velocity excited by an infinitesimal dipole (which predicts much longer time durations) nor the theory based on magnetic field nonuniformity limitations of non-longitudinal plasma waves (which requires the wave length of the oscillations to be much greater than the excitation volume), gives a proper interpretation of the high order nf_H resonance observations. It is suggested that the high order nf_H responses may be the result of the decay of an instability in the turbulent plasma caused by the high power sounder pulse.

1. INTRODUCTION

The most prominent feature of the plasma resonances observed in the topside ionosphere by the Alouette I, Alouette II, and ISIS-I satellites is their long time duration. In many cases these resonances are the most dominant feature of the topside ionogram, and they often provide the only means of obtaining ionospheric information from complex ionograms - such as those observed in high latitude regions [Hagg, Hewens, and Nelms, 1969]. There has been a considerable amount of theoretical work put forward to explain the various resonant phenomena observed on the topside ionograms. For some of the resonances, the theory agrees very well with the observations (see Graff [1971] and Benson [1971a], and references therein, for the resonance observed near the plasma frequency f_N and Graff [1970], and references therein, for the resonance observed near the upper hybrid frequency f_T); for other resonances, different theoretical approaches have yielded incompatible conclusions and further observations are required to clarify the picture (see Shkarofsky [1968], and references therein, for the resonances at the harmonics of the electron cyclotron frequency f_H). Since the resonant time duration is one of the major observable features of these resonances, it must be properly treated in any complete theoretical interpretation. It is the purpose of this paper to present Alouette I and II observations that describe the variations of the resonant time durations, for the principal resonances, resulting from variations in plasma conditions and to compare the observations with existing theories. Here the principal resonances are considered to be the resonances observed near f_N, f_T, f_H, and

nf_H where $n = 2, 3, \cdots$. See Calvert [1969] and Calvert and McAfee [1969] for comprehensive reviews of these resonances.

The first investigation of the resonant time durations was made by Fejer and Calvert [1964]. They measured the durations on several hundred Alouette I ionograms and expressed the results in terms of the plasma parameter f_N/f_H; they considered the observed variations to be in rough agreement with their theoretical predictions. Lockwood [1965] found that the number of nf_H resonances observed on a given ionogram is a maximum when the radiating antenna is parallel to the earth's magnetic field vector $\vec{B}$, and that the duration of the resonances corresponding to low n values decreases when the radiating antenna is perpendicular to $\vec{B}$. Benson [1970] measured the resonant time duration on ionograms corresponding to Alouette I data from five small spatial regions between the dip pole and the dip equator and found that the time duration of the nf_H resonances with $n \geq 3$ increased as the angle β between the satellite velocity vector $\vec{V}_{sat}$ and $\vec{B}$ decreased. Shkarofsky [1968] interpreted this variation in the observed resonant time duration as a magnetic latitude effect. It will be shown here, however, that his theoretical predictions do not agree with the observations; in addition, the dependence of the observed resonant time durations on altitude and the plasma parameter f_N/f_H will be presented.

2. INSTRUMENTAL EFFECTS

There are several properties of the Alouette I and II sounder systems that must be considered in an investigation of the time durations of plasma

resonances. These instrumental effects will be discussed separately below (for references, see Franklin [1970] and Franklin and Maclean [1969]:

1. Antenna Systems. The Alouette I and Alouette II satellites each have a system of crossed dipoles of different length to cover the sounder frequency range (0.5 to 12 MHz on Alouette I and 0.2 to 14.5 MHz on Alouette II). The crossover frequency from the long dipole (tip-to-tip length of 45.7m on Alouette I and 73.2m on Alouette II) to the short dipole (tip-to-tip length of 22.9m on both satellites) is 4.7 MHz on Alouette I and 4.6 MHz on Alouette II. These parameters are required to determine the travel time corresponding to a satellite motion equivalent to the tip-to-tip antenna length which is of particular importance when resonances attributed to plasma waves of zero group velocity are investigated. The antenna systems on both satellites are characterized by a mismatch loss that increases steadily with decreasing frequency below a low frequency cutoff (1.5 MHz on Alouette I and 2.0 MHz on Alouette II); the rate of decrease is much slower on Alouette II than on Alouette I.

2. Output power vs. frequency. The Alouette I transmitter output power decreases drastically below 1.0 MHz; it is down from 100 w by about 20 db at 0.9 MHz and by about 80 db at frequencies below 0.85 MHz (C. Franklin, private communication 1971). The Alouette II low frequency output is nearly constant down to 0.2 MHz for the high power (300 w) transmitter (which was in operation nearly 100% of the sounder operating time up until its failure on 11 May 1969). The low frequency output of the low power (100 w) Alouette II transmitter is identical to that of the Alouette I transmitter (C. Franklin, private communication 1971). (The low power Alouette I transmitter has been in operation since 12 May 1969.) These

transmitter power output characteristics in addition to the antenna system mismatch loss characteristics discussed in (1) above, must be considered when the durations of resonances observed at different frequencies are being compared.

3. Automatic gain control (AGC). The AGC time constants are different for Alouette I and Alouette II and are different for the high and low frequency portions of the Alouette II frequency sweep range (12 msec on attack and 46 msec on decay for Alouette I; 520 msec on attack and 120 msec on decay below 2.0 MHz, and 60 msec on attack and 12 msec on decay above 2.0 MHz for Alouette II). These differences must be considered when comparing the time durations of resonances observed on Alouette I with those observed on Alouette II, and when comparing Alouette II resonances observed below 2.0 MHz with those observed above 2.0 MHz.

4. Frequency resolution. The frequency resolution, i. e., the frequency spacing between sounder pulses, is determined by the frequency sweep rate divided by the pulse repetition frequency. The resolution for Alouette I varies from 15 to 20 kHz over the frequency range of the sounder. The resolution for Alouette II varies from 3.2 to 5.4 kHz in the frequency range below 2.0 MHz, and is about 31 kHz in the frequency range above 2.0 MHz. (The above Alouette I and low frequency Alouette II values are based on measurements using the expanded sounder-receiver amplitude vs. time format with a 3rd degree interpolation between frequency markers.) These differences in frequency resolution must also be considered when comparing resonant durations observed on Alouette I and Alouette II. The decrease in frequency resolution by approximately a factor of 8 and the decrease in the AGC time constant by approximately a

factor of 10 as the Alouette II sounder frequency crosses 2.0 MHz, combine to produce a dramatic effective decrease in the receiver gain for plasma resonance studies in the frequency range above 2.0 MHz on Alouette II ionograms.

5. Maximum observation time. The maximum observation time from the ionogram format is 10.2 msec for Alouette I and 30.0 msec for Alouette II.

6. Frequency markers. When the frequency of a plasma resonance coincides with an ionogram frequency marker, a reliable time duration measurement cannot be made from the ionogram format.

3. DEPENDENCE OF RESONANT TIME DURATION ON LATITUDE

The Alouette I satellite is best suited for latitude studies of plasma resonances since it is in a nearly circular orbit (perigee of 996 km and apogee of 1031 km). Ten northbound Alouette I satellite passes over the same longitude region were selected for investigation. The main selection criterion was that $\vec{V}_{sat}$ be nearly parallel to $\vec{B}$ at the dip equator; this condition is satisfied (within a few degrees) on some of the passes over the Quito telemetry station. All the available data from the same passes, as recorded by the stations to the north of Quito, were analyzed in an attempt to observe the latitudinal variations in the resonant time duration for each of the principal resonances; the frequencies and durations of these resonances were measured on every ionogram between the dip equator and the dip pole (more than 500 ionograms were scaled).

The ionogram time was used to calculate the angle between $\vec{V}_{sat}$ and $\vec{B}$ from the available orbital information.

The scaled values from the above investigation are presented in Figures 1a and 1b in the form of the resonant time duration vs. the plasma parameter f_N/f_H, $|\cos \beta|$, and $|\cos$ (dipole latitude)$|$. The plasma parameter f_N/f_H is of importance because it influences the shape of the dispersion curves of the plasma waves that are considered to be the cause of the resonances. The angle β is of importance to all resonance models that include the motion of the satellite, and the dipole latitude is of importance because the only resonance model to consider the variations of duration with latitude is based on a magnetic-latitude effect. The vertical scatter of the data points is attributed to the satellite spin-thus only the envelope of the maximum points (corresponding to optimum antenna orientation for the resonance under consideration) is of interest. The main features of Figures 1a and 1b are summarized below for each resonance:

<u>f_N resonance.</u> Strong resonances are observed only in the low latitude regions; this observation is consistent with the earlier observations of Benson [1970] but it can be interpreted in terms of the theoretical predictions of McAfee [1970], with supporting observations of Benson [1971a], that long duration f_N resonances are only observed when $f_N > f_H$ since this condition is only satisfied in low latitudes for the present data.

<u>f_T resonance.</u> Strong resonances are observed when $f_T < 2f_H$, i. e., $f_N/f_H < \sqrt{3}$, and weak resonances are observed when $f_T > 2f_H$; this observation is consistent with the earlier observations of Fejer and Calvert [1964]. No significant latitude effect is observed.

$2f_T$ resonance. Resonances are observed only when the strong form of the f_T resonance is observed, i.e., only when $f_T < 2f_H$; this observation is consistent with the earlier observations of Fejer and Calvert [1964].

f_H resonance. The observed decrease in duration with decreasing latitude is an instrumental effect (as the frequency of f_H decreases from approximately 1.0 MHz in the high latitude region to approximately 0.5 MHz in the low latitude region the Alouette I antenna system missmatch loss increases by approximately 25db (estimate based on free space measurements), and the output of the transmitter decreases by approximately 80 db).

$2f_H$ resonance. No significant change in duration is observed when the value of f_N/f_H crosses $\sqrt{3}$ (corresponding to $2f_H = f_T$); no significant latitude changes are observed.

$3f_H$, $4f_H$, and $5f_H$ resonances. These resonances are observed at all magnetic latitudes (but less frequently at high latitudes for $5f_H$). There is a strong peaking in the resonant duration as $\cos \beta \to 1$ ($\vec{V}_{sat}$ and $\vec{B}$ tend toward a parallel configuration); the peaking is even sharper as $|\cos$ (dipole latitude)$| \to 1$ (observation points tend toward the dipole equator). The duration peak near $f_N/f_H = 2.3$ is simply a dipole latitude effect since it can be seen from the figure that strong resonances were not observed away from the low latitude region.

$6f_H$ to $9f_H$ resonances. These resonances are observed only in low magnetic latitudes, they are observed more frequently near the dipole equator, and they are the strongest (especially for n = 6, 7 and 8) near the dipole equator.

<u>$10f_H$ to $14f_H$ resonances.</u> These resonances are observed only in low magnetic latitudes. The number of observations in each case and the preference of occurrence at the dipole equator is indicated in Table 1. Cyclotron harmonic resonances with $n > 14$ were not observed in the present data sample.

<u>Low latitude duration peak.</u> The most striking feature on the nf_H data presented in Figures 1a and 1b is the strong peaking of the resonant duration as $\cos\beta \to 1$ for n = 3, 4, and 5 (and to a lesser extent for n = 6, 7, and 8), and the even stronger peaking as $|\cos\text{(dipole latitude)}| \to 1$, while no significant latitude effect is observed for n = 2. These observations are consistent with an earlier study based on $\cos\beta$ [Benson, 1970]. The sharper peaking effect with the dipole latitude than with β is to be expected since the former angle is always less than or equal to the latter angle. At first glance, the above observations appear to support the theoretical work of Shkarofsky [1968] that attributes the latitude variations of the durations of the nf_H resonances, with $n \geq 3$, to the nonuniformity of the magnetic field along a field line. His theory predicts that long duration resonances should only be observed in the immediate vicinity (i. e., a few tenths of a degree) of the magnetic equator. Figure 2 presents the theoretical prediction of Shkarofsky, the maximum duration values from a previous study [Benson, 1970], and the data points from the present study on a log-log presentation of resonant duration vs. $|\cos\text{(dipole colatitude)}|$ (as was used by Shkarofsky) for the nf_H resonances with n = 3 to n = 8. (Note that the dipole colatitude is used in Figure 2 whereas the dipole latitude was used in Figure 1). The dashed lines in the figure represent the envelope of the maximum values observed for each resonance in the present study; the vertical scatter of the points is due to an antenna orientation effect and is not of interest here. The variation of the

maximum duration time with dipole latitude is much flatter in the low latitude region (| cosine (dipole colatitude) | $\lesssim$ 0.2) than is predicted by Shkarofsky. The maximum values from a previous investigation, as represented by the blocks in Figure 2, are consistent with the above statement (the one apparent exception is the high value for the point near the dipole equator at $6f_H$; this value, however, appears to be an anomalously high value [see the QUI data of Figure 6 of Benson, 1970]).

Resonant duration vs. n. A second point of disagreement between Shkarofsky's theory and the observations is found between the predicted and observed variation of resonant duration with harmonic number n at a fixed latitude. His theory predicts that the resonant duration is proportional to $n^{-1/2}$; the observed dependence (see Figure 3) is very nearly proportional to n^{-2}. The duration values presented in Figure 3 represent maximum values from a large number of observations corresponding to the same absolute value of dipole latitude (12°). (Note: the dependence of duration on n cannot be obtained from a single ionogram because of satellite spin). The curves in Figure 3 represent least squares fits of the data points to $D = An^{-2}$ where D is the maximum resonant duration and A is a constant.

Plasma wave group velocity. In attempting to explain the observed latitudinal dependence of the nf_H resonant time durations (for $n > 2$) it is important to consider the ability to match the group velocities of the plasma waves attributed to these resonances to the satellite velocity. These waves have been considered to be longitudinal waves by Crawford, Kino, and Weiss [1964], Fejer and Calvert [1964], and Sturrock [1965] with the propagation vector $\vec{k}$ directed perpendicular

to $\vec{B}$. In this case the plasma wave group velocity $\vec{V}_g$ is also directed perpendicular to $\vec{B}$ and the quantity of interest is the ratio $(V_g)_{max}/(V_{sat})_\perp$ where $(V_{sat})_\perp$ is the component of $\vec{V}_{sat}$ perpendicular to $\vec{B}$; when this ratio is greater than unity it is possible to obtain a matched condition that could account for the long time durations observed for the topside resonances. Shkarofsky and Johnston [1965] and Shkarofsky [1968] stressed this matching concept but erroneously concluded that a matched condition could not be obtained for longitudinal waves with $n > 4$ in the topside ionosphere. In support of this statement, consider the dispersion equation for longitudinal waves propagating perpendicular to $\vec{B}$ as given by Stix [Chapter 9, equation 105, 1962]:

$$\frac{\lambda}{2\left(\frac{\omega_N}{\omega_H}\right)^2} = \sum_{m=1}^{\infty} \frac{e^{-\lambda} I_m(\lambda)}{\left(\frac{\omega}{m\omega_H}\right)^2 - 1}; \tag{1}$$

differentiation with respect to k yields:

$$\frac{V_g}{V_t} = \frac{kR}{\left(\frac{\omega}{\omega_H}\right)} \left\{ \frac{\left(\sum_{m=1}^{\infty} \frac{e^{-\lambda} I_{m+1}(\lambda) + \frac{m-\lambda}{\lambda} I_m(\lambda)\, e^{-\lambda}}{\left(\frac{\omega}{m\omega_H}\right)^2 - 1} \right) - \frac{1}{2\left(\frac{\omega_N}{\omega_H}\right)^2}}{\sum_{m=1}^{\infty} \frac{e^{-\lambda} I_m(\lambda)}{m^2 \left[\left(\frac{\omega}{m\omega_H}\right)^2 - 1\right]^2}} \right\} \tag{2}$$

where

$V_g = \partial\omega/\partial k$ is the plasma wave group velocity

$V_t = R\omega_H = (\kappa T_e/m_e)^{1/2}$ is the electron thermal velocity (κ is Boltzmann's constant, T_e is the electron temperature, and m_e is the electron mass)

R is the electron cyclotron radius

$\lambda = k^2 R^2$

ω, ω_H, and ω_N = $2\pi f$, $2\pi f_H$, and $2\pi f_N$, respectively

$I_m(\lambda)$ is the modified Bessel function.

The ratio $V_g/(V_{sat})_\perp$ was calculated for the nf_H resonances with $n \geq 4$ from (2) using T_e values from the Alouette I electrostatic probe experiment and $(V_{sat})_\perp$ values as determined from the orbital information corresponding to the data used in this study; the results for the maximum value of this ratio are presented in Figure 4. There are two main points to note in Figure 4: first, it is not difficult to obtain a matching between V_g and $(V_{sat})_\perp$ in the topside ionosphere for the nf_H resonances with $n > 4$ (e. g., matching is possible for $n = 7$ when $\cos\beta > 0.8$) and second, it is difficult to explain the observed latitudinal variations in resonant duration strictly in terms of a matching concept (e. g., the durations of the $4f_H$ and $5f_H$ resonances begin to increase when $\cos\beta$ exceeds about 0.6 (see Figure 1b), whereas matching for these resonances is obtained when $\cos\beta$ exceeds 0.36 and 0.54, respectively; also, the $n = 7$ through $n = 11$ resonances are observed when $\cos\beta$ exceeds about 0.65 (see Figure 1b), whereas matching is only obtained when $\cos\beta$ exceeds 0.805, 0.865, 0.902, 0.932, and 0.956 for n = 7, 8, 9, 10, and 11, respectively).

Instrumental effects. There are two features of the latitudinal variations of the nf_H resonant durations in Figure 1b that can be attributed to instrumental effects. First, the lack of observations of the nf_H resonances with $n \geq 6$ in the high latitude region is due to the change over from the long antenna (in low latitudes) to the short antenna (in high latitudes) as can be seen from Figure 5 where the effective domains of the two antennas are shown as a function of $\cos\beta$

for the present data. (Note that the $5f_H$ resonance is very close to the transition region between the two antenna domains in the high latitude regions, and that $5f_H$ resonances are only occasionally observed in high latitudes). Second, the occurrence of very high harmonic resonances (n = 12 of Figure 1b and n = 14 of table 1) are more sensitive to antenna orientation than to the condition $\cos \beta = 1$ or $|\cos$ (dipole latitude)$| = 1$. This statement is based on the results of Lockwood (1965) and the present observations.

4. DEPENDENCE OF RESONANT TIME DURATION ON ALTITUDE

An inspection of Alouette II ionograms corresponding to apogee (near 500 km) and perigee (near 3000 km), with the same value of $\cos \beta$, indicate a definite dependence of the resonant time duration on altitude for some of the principal resonances. This altitude dependence is very apparent for the f_H resonances on the apogee and perigee ionograms shown in Figures 6a and 6b, respectively; the duration is much longer at apogee than perigee even though the antenna missmatch loss is greater in the former case because f_H is at a lower frequency. An investigation of Alouette II ionograms was conducted to determine which of the principal resonance durations depend on altitude and whether this dependence is the result of the variation of the plasma parameter f_N/f_H or strictly an altitude effect. In order to eliminate the strong latitude effect discussed in the previous section, only those ionograms corresponding to the condition $\cos \beta \approx 1$ (where strong resonances are observed - see Figures 1a and 1b) were considered. The resonant durations were scaled on ionograms between perigee and apogee in

steps of 500 km. The results are presented in Figures 7a and 7b in the form of resonant duration vs. f_N/f_H and height for the resonances observed at f_N, f_T, f_H, and nf_H with n = 2 through 12; the vertical scatter of the points is partly the result of satellite spin and partly the result of variations in height (on the f_N/f_H presentations) and f_N/f_H (on the height presentations). For the present moment, neglect the points enclosed by solid lines.

Consider first the resonances shown in Figure 7a. The low duration observed for the f_N resonance at 500 km ($f_N/f_H > 7.2$) is an instrumental effect. (The resonances at 500 km were recorded at frequencies above 2.0 MHz while the resonances corresponding to higher altitudes were recorded at frequencies below 2.0 MHz; the effective gain of the receiver is much less in the former case than it is in the latter case). The f_T resonance shows no apparent altitude dependence. The lack of observations at 500 km is the result of the masking of the f_T resonance by the f_N resonance. The f_H resonance definitely shows a stronger dependence of resonant duration on altitude than on f_N/f_H (note that no resonance persisted longer than 7 msec at 500 km and that many resonances of short duration were observed when $f_N/f_H \lesssim 4$), whereas the $2f_H$ resonance definitely shows a stronger dependence of resonant duration on f_N/f_H than on altitude (note that several resonances persisted longer than 8 msec at 500 km and that these resonances all corresponded to relatively low values of f_N/f_H, i. e., $f_N/f_H \lesssim 8$; also, no resonances of short duration were observed when $f_N/f_H \lesssim 4$). As in the case of Alouette I, the envelope of the maximum is of main interest (the vertical scatter of the data points is mainly due to antenna spin). For the $2f_H$ resonance, this envelope is well described by the curve on the duration vs. f_N/f_H plot which corresponds to a least squares fit of 4 representative maximum values of the

500 km data points to $D = A\ (f_N/f_H)^{-1}$ where A is a constant. Only the 500 km points were considered in the curve fit because they correspond to the largest variation in f_N/f_H (3.7 to 16.1) while maintaining a nearly constant value for f_H and hence a nearly constant sounder frequency response.

Next, consider the resonances shown in Figure 7b. The resonances at $3f_H$ and $4f_H$ show a definite dependence of resonant duration on altitude (duration increases with increasing altitude), higher order harmonics are consistently observed only at 500 km, and there is an abrupt cut-off of resonances with $n > 7$ at 3000 km. This cut-off is an instrumental effect as can be seen by an inspection of Figure 8 where representative frequencies of the various nf_H resonances are presented as a function of altitude. The domains of the short and long antennas are indicated on the figure together with a dotted line at 2.0 MHz corresponding to the transition frequency between high and low frequency resolution (see "Instrumental Effects" parts 3 and 4). At 3000 km the resonances with $n \leq 7$ are observed in the frequency region below 2.0 MHz while the resonances with $n > 7$ are observed in the frequency region above 2.0 MHz; the lower effective receiver gain in the latter case explains the sudden drop in the frequency of occurrence of the resonances with $n > 7$. At 2500 km the $n = 6$ resonance represents a transition between the situation of high effective receiver gain and low effective receiver gain in that 43% of the ionograms in this region correspond to the condition $6f_H > 2.0$ MHz and they did not contain $6f_H$ resonances. Similarly, at 2000 km resonances with $n > 5$ were not observed because they appeared in the frequency region above 2.0 MHz. For lower altitudes, on the other hand, the lower effective receiver gain in the frequency region above 2.0 MHz did not always prevent the detection of high order harmonic resonances. For example,

at 1500 km the $5f_H$ resonance was observed even though $5f_H > 2.0$ MHz for all of the ionograms sampled in this height range, at 1000 km resonances with $n \geq 4$ were observed even though 50% of the $n = 4$ resonances (including 2 of the 5 with durations of 6 msec or more) and all of the resonances with $n > 4$ corresponded to $nf_H > 2.0$ MHz, and at 500 km all of the resonances with $n \geq 4$ were observed with $nf_H > 2.0$ MHz.

The increase in the maximum duration of the $3f_H$ resonance with increasing altitude is not an instrumental effect since all the observations (except for one of the 500 km points) correspond to a high effective sounder gain, i.e., $f < 2.0$ MHz, and the antenna mismatch loss is greater at the high altitudes than at the lower altitudes; thus the true increase may be slightly greater than indicated by the figure. Similar comments hold for the $4f_H$ resonances from 1500 to 3000 km; the maximum durations of 500 and 1000 km were limited by the reduced gain of the sounder system (see Figure 8). (Note: the 30 msec values at 3000 km for $n = 3$ and the 12 msec value at 500 km for $n = 4$ are anomalously high due to proton gyro effects observed when the exit frequency $f_z S$ for the z wave is near nf_H - this enhancement will be discussed in a separate paper). The $5f_H$ resonance shows a definite enhancement in duration at 500 km, as compared with 1000 and 1500 km, and a definite enhancement at 3000 km, as compared with 2000 and 2500 km; these comparisons are chosen because the effective gain of the sounder system is greater at 2000, 2500, and 3000 km than at 500, 1000, and 1500 km (see Figure 8). This enhancement at 500 km is even more apparent on the $6f_H$ resonance where, <u>in spite of the reduced gain,</u> the maximum duration at 500 km is observed to be a factor of two greater than the maximum duration at 3000 km. Similar comments hold for the $n = 7$ resonance where

resonances are still consistently observed at 3000 km. The maximum durations for the higher order harmonics are greater at 500 km than at any other altitude where these resonances are observed.

Absorption of the f_H wave. The observed dependence of resonant duration on altitude when $\cos\beta \approx 1$ suggests a dependence on the local plasma conditions. The electron density, electron temperature T_e, and electron-ion collision frequency ν_{ei} corresponding to the Alouette II data of Figures 7a and 7b are presented in Table 2. The electron neutral collision frequency ν_{en} is not shown because it is several orders of magnitude smaller than ν_{ei} (e. g., $\nu_{en} = 1\ \mathrm{sec}^{-1}$ at 500 km). The values given in the table are representative values for each data set. When inspecting these values, one must keep in mind that the low altitudes (500 and 1000 km) correspond to daytime conditions whereas the higher altitudes correspond to nighttime conditions. The quantities N and ν_{ei} decrease by more than an order of magnitude between 500 and 1000 km and by more than a factor of 2 between 1000 and 1500 km; they are relatively constant between 1500 and 3000 km.

The above variations of N and ν_{ei} appear to be more closely related to the observed variation of the f_H resonant duration with height than to any of the other resonances (see Figures 7a and 7b). Thus, long duration f_H resonances are only observed in a very rare plasma. This observation supports the conclusion of Oya [1971], based on an analysis of the sequence of diffuse resonances observed on topside ionograms [Oya, 1970], that the f_H wave is quickly absorbed by the medium. It also indicates the importance of the f_H resonance in the determination of N in a rare plasma using the beat frequency method introduced by Hagg [1967], providing that the dispersion

effects associated with the f_H and f_T waves (the two beating waves in the Hagg method) can be determined [Benson, 1971b], and in the determination of the ambient value of $|\vec{B}|$ when the higher order harmonics are not present.

Resonances observed under conditions of reduced sounder transmitter power. The points enclosed by solid lines in Figures 7a and 7b correspond to four consecutive ionograms from a single satellite pass when the low power transmitter was in operation (all other points correspond to the high power transmitter). Figure 9 presents a comparison between one of these four ionograms and an ionogram from the same data set recorded under normal high power operation. Below 1.0 MHz the resonances recorded during low power operation (top) are severely reduced in time duration compared to those recorded during high power operation (bottom); above 1.0 MHz there is very little difference between the two records. The frequency 1.0 MHz is significant because the low power transmitter has a sudden drop in output power below 1.0 MHz (see the discussion in the section entitled "Instrumental Effects"). Thus, the resonances of Figure 7a (which were recorded at frequencies below 1.0 MHz) are greatly reduced while the resonances of Figure 7b (which were recorded at frequencies above 1.0 MHz) are not affected (e. g., the strongest $3f_H$ resonance was obtained from one of the four "low power" ionograms). The main feature of interest in the above comparison is the f_N resonance. This resonance has been attributed to two oblique plasma wave echoes that produce a strong resonance with a beat pattern when $f_N > f_H$, and to one oblique echo that produces a weak resonance when $f_N < f_H$ [McAfee, 1970]. The typical strong pattern is revealed in the lower part of Figure 9; the top part of the figure reveals a typical weak pattern [Benson, 1971a] even though the weak pattern condition $f_N < f_H$ is not satisfied.

Thus the excitation of the strong pattern is dependent on the output power in addition to the plasma parameter f_N/f_H, and a low power transmitter is capable of producing only one of the two waves necessary to obtain a beat pattern which is required for electron temperature measurements using the procedure introduced by Warnock, McAfee, and Thompson [1970]. An investigation of the sequence of ionograms that contained the top ionogram of Figure 9, revealed that the strong f_N pattern was not produced until an effective power output (into a 400 Ω load) of approximately 0.5 w was attained.

5. TEMPORAL AND SPATIAL VARIATIONS AND RESONANT VOLUME FOR THE HIGHER nf_H RESONANCES

One of the problems in the interpretation of the observed resonant time durations is to distinguish between the decay of the signal in time and the decay due to the motion of the satellite from the region of original excitation. Sturrock [1965] suggested that the nf_H resonant time durations were limited by the above spatial effect. Benson [1970] emphasized that this concept is consistent with the Alouette I observations for the resonances with $n > 4$ and that there is no need to invoke the concept of matching $\vec{V}_g$ to $\vec{V}_{sat}$ [Shkarofsky and Johnston, 1965] for these resonances. Shkarofsky [1968] predicted the time durations for the resonances with $n \geq 3$, based on the matching concept, but the resulting variation of duration time with latitude and with n does not agree with the observations (see Section 3).

__Temporal variations.__ Observational evidence pertaining to the above problem can be obtained by comparing the Alouette I and Alouette II results since different antenna lengths were employed on the two satellites; this difference should effect the resonant time duration if this duration is determined by the motion of the satellite through an initial excitation region. The observations of interest are the Alouette I data with $\cos\beta \approx 1$ and the Alouette II data with $\cos\beta \approx 1$ at 1000 km (since the Alouette I data corresponds to a 1000 km altitude). These observations are summarized in Table 3 for the nf_H resonances from $n = 3$ to $n = 8$ together with the effective radiated sounder power; the resonances at $n = 1$, $n = 2$ and $n > 8$ were omitted because of the difficulties in making a meaningful comparison between the two data sets for these resonances (the Alouette I $n = 1$ resonance is not observed when $\cos\beta = 1$ due to instrumental limitations, the Alouette II $n = 2$ resonances of longest duration at 1000 km were equal to the observational upper limit, and only one ionogram from the Alouette II 1000 km data sample contained resonances with $n > 8$). The following statements can be made concerning the data comparison presented in Table 3:

1. The resonant durations are greater on Alouette II only in the frequency range below 2.0 MHz where the Alouette II receiving system has a much higher effective gain than the Alouette I system; thus the Alouette I power is sufficient to excite high order nf_H resonances and the increased Alouette II power does not produce resonances of longer time duration.

2. The slightly greater duration values observed on Alouette I in the frequency region above 2.0 MHz may be attributed to receiver characteristics (see comments under * in Table 3) and/or to the larger Alouette I data sample which increases the probability of favorable conditions for the detection of

strong high order nf_H resonances, i.e., the condition where the radiating antenna is nearly parallel to $\vec{B}$ [Lockwood, 1965].

Statement number 2 is of special interest to the present discussion because the resonant durations would be expected to be 50% greater on Alouette II than on Alouette I if they are determined by the motion of the satellite with respect to a stationary resonant volume. This expectation follows from the manner in which the data were sampled, i. e., $\vec{V}_{sat}$ restricted to a direction within 10° of $\vec{B}$ ($\cos \beta \geq 0.985$) which requires the antenna to be nearly parallel to $\vec{V}_{sat}$ for the detection of the higher order nf_H resonances. The time required for the satellite to move a distance equal to the tip-to-tip length of the long antenna corresponding to the present data samples was 6.2(5) msec on Alouette I and 9.5 msec on Alouette II. For each satellite, however, the maximum observed duration for the resonances with $n > 4$ were less than the corresponding antenna length transit time (which supports the earlier conclusions [Benson, 1970] that the matching concept is not required for these resonances). Since the average durations are considerably smaller than this time (approximately by an order of magnitude), and no dependence on the antenna length is evident, it appears that the motion of the satellite is not a major factor in limiting the observation of high order harmonic resonances in low latitudes; thus, the duration of these resonances is determined by a time decay.

Spatial Variations. The presence of high order nf_H resonances in high latitudes when the observing frequency corresponds to the domain of the long antenna, and the absence of these resonances when the observing frequency corresponds to the domain of the short antenna (see Figures 1b and 5) supports

the conclusion of Benson [1970] that these resonances are not observed in high latitudes because of the motion of the satellite from a small region of resonant excitation, i. e., the region is smaller for the short antenna than for the long antenna. Since the antenna is aligned nearly parallel to $\vec{B}$ for optimum resonance excitation, the resonant volume (assumed to be elongated along the antenna element) projects a decreasing distance along the satellite path as the satellite approaches the dip pole ($\cos\beta = 0$). When this distance becomes shorter than the satellite motion corresponding to a travel time less than the lower limit of observation, no resonances will be observed. The possibility that the high order harmonic resonances are simply not excited by the short antenna in high latitudes appears very unlikely in view of the remarkable observation cutoff for the resonances with $n > 5$ when $\cos\beta \leq 0.65$ (see Figure 1b); these resonances are excited by the short antenna when $\cos\beta = 0.65$ (see Figures 1b and 5). Thus, in high latitudes it is the motion of the satellite that prevents the detection of high order harmonic resonances.

Resonant volume. An estimate of the radial extent of the resonant volume from the antenna element can be obtained from the above observational cut-off of $\cos\beta = 0.65$ and by assuming that the antenna element is nearly parallel to $\vec{B}$ for the detection of the higher order harmonics (so that β can be considered as the angle between the antenna axis and $\vec{V}_{sat}$). Since the minimum observation time for a resonance is 0.4 msec and $\vec{V}_{sat} = 7.3$ m/msec for Alouette I, the upper limit for the resonant region associated with the short antenna and $n > 5$ must by approximately 3m in the direction of $\vec{V}_{sat}$ or approximately 2m in the radial direction from the antenna (corresponding to an angle of approximately 50° between the antenna and $\vec{V}_{sat}$, i. e., $\cos\beta = 0.65$). The excitation

volume associated with the long antenna is larger than the observational limit imposed by the satellite motion and thus the high order nf_H resonances excited by this antenna are observed in high latitudes.

The above estimate for the resonant volume is consistent with the completely independent observations of frequency shifts associated with the Alouette I and II high order nf_H resonances. The large frequency shifts observed on Alouette I have been attributed to the magnetic contamination of the spring steel antenna elements since similar shifts were not observed on Alouette II where non-magnetic Be-Cu antennas were used [Benson, 1969, 1970, and 1971b]. Magnetic measurements made on a section of the material from the same stock as was used in Alouette I indicated that the contaminant field was very strong near (15 cm) the antenna but was fairly insignificant beyond about 2m in the radial direction from the element [Benson, 1970]. The lack of extreme frequency shifts on Alouette I indicated that the resonant volume was not confined to the sheath region around the antenna. The Alouette II observations [Benson, 1971b] indicate that the Alouette I shifts (for $n > 4$) are difinitely due to magnetic contamination and not plasma wave dispersion effects; thus the resonant volume must not extend much beyond 2m from the antenna.

6. DEPENDENCE OF THE nf_H RESONANT TIME DURATION ON f_N/f_H

The data of Sections 3 and 4 were chosen primarily to investigate the dependence of resonant time duration on latitude and altitude; in order to investi-

gate the variation of resonant duration as a function of f_N/f_H for the nf_H resonances, consecutive ionograms were scaled from Alouette II satellite passes recorded under conditions of rapidly varying f_N and slowly varying f_H. This situation is desirable because the pattern of nf_H resonances remains nearly constant in frequency from one ionogram to the next which reduces the effect of the variation in sounder response with frequency. The results of the duration scaling are presented in Figure 10 for the f_H, $2f_H$, and $3f_H$ resonances from four Alouette II passes. The scaled values correspond to resonant observations in the high resolution portion of the ionogram, i. e., below 2.0 MHz. The antenna system mismatch loss increases steadily with decreasing frequency in this region (see Section 2); the observed variation in f_H is given for each pass in the bottom row and it must be considered when investigating the variations in resonant duration of the resonances given in the same column, i. e., corresponding to the same pass. Also given in the bottom row are the variations of $\cos\beta$ and H since these parameters can influence the resonant duration (see Sections 3 and 4); for further information on the orbital and plasma conditions pertaining to these satellite passes, see Figures 1 and 2 of Benson [1971b]. The main features of Figure 10 will be discussed below for each resonance separately:

<u>f_H resonance (top row)</u>: There is no detectable change in the f_H resonant duration as the plasma conditions change from $f_N/f_H < 1$ to $f_N/f_H > 1$ (see pass 1927 of Figure 10), whereas there is a dramatic change in the f_N resonant duration (see Figure 1 of Benson [1971a]). The f_H resonant duration is extremely long in the rarefied plasma encountered during pass 1927, e. g., $D \approx 20$ msec when $N \approx 580\ cm^{-3}$ corresponding to $f_N/f_H \approx 0.3$, even though $\cos\beta \to 0$ (the nf_H resonances with $n > 2$ are not observed with long durations when $\cos\beta \to 0$, see

Figure 1b). The decrease of duration with increasing f_N/f_H can be attributed to the increasing mismatch loss as the f_H frequency decreases and to the decreasing height of the satellite. The effect of the increase in cos β is more difficult to interpret because the cos β dependence could not be determined for the f_H resonance from the Alouette I data (see Section 3). The data from passes 1785, 1844 and (to a lesser extent) 4086 provide some evidence that the f_H resonant duration increases with increasing cos β, i.e., the effect of the decreasing f_H and H curves on the duration may be offset to some extent by the effect of the increasing cos β curve to produce the nearly flat distribution of data points on these passes. In any event, it is difficult to establish a definite dependence of the f_H duration on f_N/f_H, e. g., above about $f_N/f_H = 3$ on pass 1785 the effect of increasing f_H and decreasing H are opposing one another and it is difficult to interpret the variations in duration.

<u>$2f_H$ resonance (2nd row in Figure 10):</u> There is no detectable change in the $2f_H$ resonant duration as the plasma conditions change from $f_T < 2f_H$, i. e., $f_N/f_H < \sqrt{3}$, to $f_T > 2f_H$ (see all four passes of Figure 10); this observation is in agreement with the Alouette I observations of Section 3 (see Figure 1a). The $2f_H$ resonant duration decreases fairly continuously on pass 1927 as $f_N/f_H \rightarrow 0$ in spite of a relatively low antenna mismatch loss (10 db for $2f_H \approx 1.5$ MHz) and favorable height conditions (see Figure 7a with H between 1500 and 2000 km). Since the duration for this resonance is not sensitive to cos β (see Figure 1a), it appears that it decreases with decreasing f_N. This conclusion is supported by an inspection of ionograms recorded under conditions of lower f_N than the conditions corresponding to pass 1927 of Figure 10 (where $(f_N)_{min} \approx 0.2$ MHz). When $f_N < 0.1$ MHz the f_T and the f_H resonances nearly overlap one another and a beat frequency signal is

often observed on the ionogram structure that appears as a single resonance [Hagg, 1967]. On these ionograms corresponding to low electron density (the exact values are uncertain due to plasma wave dispersion effects, but they may be as low as, or lower than, 100 cm^{-3} [Benson, 1971b]) the $2f_H$ resonance is always observed to have a short time duration [e. g., Hagg, 1967, Figures 2 and 3; Hagg, Hewens, and Nelms, 1969, Figure 12; Timleck and Nelms, 1969, Figure 1]. Since the data of Figure 7a indicate a decrease in duration with increasing f_N/f_H when $f_N/f_H \gtrsim 4$, there must be a peak duration value corresponding to $f_N/f_H < 4$. The exact location of the peak is difficult to determine from the present data because of the dependence of the duration on the observing frequency and on H. The data from Figure 10 indicate that the peak occurs in the region $f_N/f_H > 2$ if the variations in antenna mismatch loss are considered, e. g., on pass 1785 the mismatch loss is 19 db (for $2f_H$ = .91 MHz) when f_N/f_H = 2.5 compared with a loss of only 15 db (for $2f_H$ = 1.15 MHz) when f_N/f_H = 1.0.

<u>$3f_H$ resonance (3rd row in Figure 10):</u> There is no detectable change in the $3f_H$ resonant duration as the plasma conditions change from $f_T < 3f_H$, i. e., $f_N/f_H < \sqrt{8}$, to $f_T > 3f_H$. The duration decreases as f_N/f_H decreases even though the increasing f_H and H curves produce effects that favor long resonance durations (see Section 2 and Figure 7b). This decrease is attributed to a decrease in f_N rather than to a decrease in $\cos \beta$ since the $3f_H$ resonant duration is fairly constant (and short) when $\cos \beta \lesssim 0.5$ (see Figure 1b). This conclusion is also supported by an inspection of high latitude ionograms recorded under conditions of very low N. On such ionograms, where the Hagg beat phenomenon is observed, the $3f_H$ resonance is seldom, if ever, observed [e. g., Hagg, Hewens, and Nelms, 1969, Figure 12]. In fact, the $3f_H$ resonance will often appear to flicker in and

out as a series of ionograms, some of which contain the Hagg beat phenomenon, are viewed rapidly, i. e., the $3f_H$ resonance can often be detected on those ionograms where N is not low enough to produce the Hagg beat, but cannot be detected when the beat is observed. The data presented in Figure 7b indicate that a very rarefied plasma is required to produce long duration $3f_H$ resonances near the dipole equator, but the high latitude data indicates that there must be a sufficient number of electrons to produce a detectable resonant signal; thus the increase in duration with increasing altitude over the vicinity of the dipole equator, as indicated in Figure 7b, must terminate at some altitude above the 3000 km apogee of Alouette II.

7. COMPARISON OF OBSERVATIONS WITH EXISTING THEORIES

In Section 3 it was shown that the latitude variation of duration, and the variation of duration with n, for the nf_H resonances with $n \geq 3$ did not agree with the theory of Shkarofsky [1968] which is based on matching of $\vec{V}_g$ to $(\vec{V}_{sat})_\perp$ for non-longitudinal plasma waves and which includes the effect of the nonuniformity of $\vec{B}$. The conclusion of Section 5 that the resonant volume extends only about 2m from the antenna for the nf_H resonances with $n > 5$ also opposes this theory which assumes that the wavelength of the resonant oscillation corresponds to the electromagnetic mode rather than to the electrostatic (longitudinal) mode; this assumption requires the wavelength to be more than an order of magnitude greater than the dimension of the resonant region from the antenna. The justification for the above choice of wavelength was that a matching of $\vec{V}_g$ to $(\vec{V}_{sat})_\perp$

was possible only for the electromagnetic modes when $n > 4$; the present results (Section 3), however, indicate that such a matching is also possible for the electrostatic modes.

The conclusion of Section 5 that the duration of the nf_H resonances with $n > 4$ is limited by a natural time decay, of approximately 2 msec or less, does not agree with the theoretical work of Sturrock [1965] and Deering and Fejer [1965], which is based on longitudinal waves of low group velocity and the infinitesimal dipole approximation, since the predicted time decays are several orders of magnitude too large.

The $2f_H$ resonant time duration peak observed when f_N/f_H is between 2 and 4 (Section 6) supports the conclusion of Oya [1971, and H. Oya, personal communication, 1971] that the $2f_H$ resonance, the diffuse resonance f_{D1} [Oya, 1970] (originally designated as f_D by Nelms and Lockwood [1967]), and the electrostatic wave resonance f_{Q3} [Warren and Hagg, 1968] are coupled in a three wave decay process since the f_{D1} resonance has a strong duration peak when f_N/f_H is in the range from 2.25 to 3.25 (corresponding to f_{D1}/f_H in the range from 1.5 to 1.63 [Oya, 1971].

Some of the discrepancies between the observations and the theoretical work as discussed in the first two paragraphs of this section, may be eliminated by including the effect of the antenna length in the theory. The conclusion based on the present observations that the resonant region is only about 1/10 of the antenna length for the higher nf_H resonances certainly indicates that such an approach is required. Another possibility is that the responses observed near nf_H for the higher harmonics (say $n > 5$) are due almost entirely to the decay of an instability in the turbulent plasma initiated by the high power sounder pulse.

The observed durations of approximately 2 msec or less for these resonances is of the same order as the 1.5 msec duration of the instability associated with the diffuse resonance [Oya, 1971].

8. SUMMARY

The main conclusions from the present study are summarized below:

f_N resonance: An effective power of approximately 0.5w is required in order to produce the strong form of the f_N resonance which is required for electron temperature determinations based on the oblique echo theory for this resonance.

f_H resonance: The f_H resonance is stronger than any of the other nf_H resonances at high altitudes in high latitudes. The low latitude altitude study shows that it is quickly absorbed in the relatively dense plasma of 500 km but that it is long lasting in the rare plasma above about 1500 km. Thus, this resonance has great potential as a diagnostic tool for determining N and $|\vec{B}|$ in a rare plasma. There is no detectable change in duration as the plasma conditions change from $f_N/f_H < 1$ to $f_N/f_H > 1$.

$2f_H$ resonance: The $2f_H$ resonance is the only nf_H resonance where the duration does not show a significant latitude dependence. The duration is observed to have a maximum between $f_N/f_H = 2$ and 4 in agreement with a recent theory proposed for the interpretation of the sequence of diffuse resonances in terms

of the nonlinear interaction of plasma waves (including the $2f_H$ wave). No significant change in the $2f_H$ resonant duration is detected as the plasma conditions change from $f_T < 2f_H$ to $f_T > 2f_H$.

nf_H resonances with $n \geq 3$: The observed latitude dependence of resonant duration for the nf_H resonances with $n \geq 3$ appears to be caused by a combination of geometrical, instrumental, and satellite motion effects closely related to the size of the resonant region rather than by magnetic field nonuniformity limitations of nonlongitudinal plasma waves, with $\vec{V}_g$ matched to $(\vec{V}_{sat})_\perp$, as has been proposed. Other disagreements with this theory are the following: the observed decrease of duration with increasing n very nearly follows a $1/n^2$ dependence rather than the predicted $1/\sqrt{n}$ dependence, and the inferred resonant region for the resonances with $n > 5$ is too small (a few meters from the antenna) to allow oscillations with wavelengths corresponding to the electromagnetic mode. It is not necessary to restrict the above matching concept to the electromagnetic modes since it is shown that a matched condition can be obtained for high order longitudinal nf_H waves in low latitudes. The resonances with $n > 4$ are observed for their full natural time decay of a few milliseconds. This short duration is several orders of magnitude less than is predicted by theories based on longitudinal waves with $\vec{V}_g \approx 0$ that are excited by an infinitesimal dipole. In view of the small extent of the resonant oscillations from the antenna, for the higher order nf_H resonances, it appears that the infinitesimal dipole approximation is not suited for a proper interpretation of the Alouette observations pertaining to these resonances. One of the most striking differences between the high order harmonic resonances (say $n \geq 6$) and the low order harmonic resonances (say $n = 3$ and 4) is that the high order resonances are observed with the longest

time durations in the relatively dense plasma at the lowest altitude sampled (500 km). The possibility that these signals may be due to a plasma instability initiated by the high power sounder pulse is suggested.

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Table 1
Number of Observations and Preference of Occurrence at the Dipole Equator for the Higher order nf_H resonances

n	Number of Resonances Observed	Preference of Occurrence at the Dipole Equator Indicated
10	8	slight
11	7	slight
12	3	no
13*	0	
14*	1	no ($\cos\beta = .7$, $\lvert\cos(\text{dipole lat})\rvert = .89$)

*Not shown in Figure 1

Table 2

Electron Density N, Electron Temperature T_e, and Electron-Ion Collision Frequency ν_{ei} Corresponding to the Alouette II Data of Figures 7a and 7b

Height (km)	$N(cm^{-3})$*	T_e(°K)**	ν_{ei} (sec^{-1})***
500	3.6×10^5	2000	210
1000	3.4×10^4	2200	19
1500	1.3×10^4	2100	8
2000	$8.3(5) \times 10^3$	1900	6
2500	6.6×10^3	1800	5
3000	7.2×10^3	1700	6

*Determined from $N \simeq f_N^2/81$ where $f_N(kH_z)$ is obtained from the ionogram f_N resonant frequency.

**Obtained from the Alouette II probe experiment.

***Determined from eq. (408) of Rishbeth and Garriott [1969].

Table 3

Comparison of Alouette I and Alouette II nf_H Resonant Time Durations when $\cos\beta = 1$ at 1000 km

n	Duration (msec)**				Effective Power Radiated(w)***	
	Alouette I		Alouette II			
	maximum	average	maximum	average	Alouette I	Alouette II
3*	10.4	5.7	19.3	8.9	20	60
4*	7.5	2.7	8.0	3.9	12	150
5	3.6	1.6	2.7	1.3	16	150
6	1.8	0.9	1.0	0.7	16	150
7	1.2	0.7	0.8	0.5	40	150
8	1.3	0.6(5)	0.7	0.6	25	150

*Resonances observed in the frequency range below 2.0 MHz where the effective gain of the sounder receiving system is much higher on Alouette II than it is on Alouette I; above 2.0 MHz (recording condition for resonances not marked by an *) the frequency resolution is greater on Alouette I and the difference between the AGC time constants on the two satellites is reduced – the Alouette II AGC system, however, is still more favorable for resonance detection (see Section 2).

**The Alouette I values correspond to the data points in Figure 1b that satisfy the condition $\cos\beta \geq 0.985$ (66 ionograms) and the Alouette II values correspond to the 1000 Km data points in Figure 7b (18 ionograms); the Alouette I $4f_H$ data points in Figure 1b corresponding to a resonance overlap condition were not considered in the derivation of the values given in the table.

***The effective power radiated is based on an assumed 400Ω load and the antenna system mismatch loss (Figures 3 and 8 of Franklin and Maclean [1969]) corresponding to the observed resonant frequency.

FIGURE CAPTIONS

Figure 1a. Resonant time duration vs. f_N/f_H, $\cos\beta$, and $|\cos$ (dipole latitude)$|$ for the Alouette I plasma resonances observed at f_N, f_T, $2f_T$, f_H, and $2f_H$. The open circles are used to indicate that the resonance under consideration was observed to overlap another resonant feature on the ionogram (e.g., see the f_N entries corresponding to long duration times with $f_N/f_H \approx 1$, $\cos\beta < 0.4$, and $|\cos$ (dipole latitude)$|$ < 0.7); the solid points correspond to observations free from such overlap effects and should be given more weight.

Figure 1b. Same as Figure 1a except for the Alouette I plasma resonances observed at nf_H with n = 3 to 12. In this figure the only points corresponding to the overlap condition are the $4f_H$ entries near $f_N/f_H \approx 4$ (corresponding to the condition $4f_H \approx f_T$).

Figure 2. Resonant time duration vs. $|\cos$ (dipole colatitude)$|$ for the Alouette I plasma resonances observed at nf_H with n = 3 to 8. The data from the present study (solid points with dashed lines indicating the envelope of the maximum) are compared with the maximum values obtained from a previous investigation [Benson, 1970], and the theoretical predictions of Shkarofsky [1968].

Figure 3. Maximum observed values of the Alouette I nf_H resonant time duration D vs. n for n = 3 to 12 when $|$dipole latitude$| = 12°$. The results presented from a previous investigation correspond to a small region near -12° dipole latitude; the results from the present investigation correspond to the maximum values expected at +12°

dipole latitude based on the trend of the low latitude data points presented in Figure 1b. The curves in each case represent a least squares fit of the points to $D = An^{-2}$ where A is a constant.

Figure 4. The ratio $(V_g)_{max}/(V_{sat})_\perp$ vs. cos β corresponding to the Alouette I data of the present investigation.

Figure 5. The frequency domains of the long and short antennas corresponding to the Alouette I data of the present investigation.

Figure 6a. An Alouette II ionogram recorded near apogee illustrating a long duration f_H resonance; f_{D1} is the first member of the sequence of diffuse resonances [Oya, 1970], f_zS is the exit frequency of the z wave, and f_xS is the exit frequency of the x wave, (QUI pass 7710, 10 September 1967, 09:42:25 UT; -14° latitude, 84° west longitude, 2922 km.

Figure 6b. An Alouette II ionogram recorded near perigee illustrating a short duration f_H resonance; f_{D2} is the second member of the sequence of diffuse resonances [Oya, 1970] (SNT pass 2316, 12 June 1966, 14:38:47 UT; -16° latitude, 71° west longitude, and 580 km).

Figure 7a. Resonant time duration vs. f_N/f_H and the height H for the Alouette II plasma resonances observed at f_N, f_T, f_H, and $2f_H$ when cos $\beta \geq 0.985$, i.e., $\beta \leq 10°$. The curve on the $2f_H$ duration vs. f_N/f_H plot represents a least squares fit of the maximum duration D observed at 500 km to $D = A(f_N/f_H)^{-1}$, where A is a constant, using the following values: D = 23.8, 10.8, 6.8, and 5.5 msec corresponding to

f_N/f_H = 3.73, 6.83, 9.77, and 15.90 respectively. The points enclosed by solid lines correspond to four ionograms recorded when the low power transmitter was in operation (see text and Figure 9).

Figure 7b. Same as Figure 7a except for the Alouette II plasma resonances observed at nf_H with n = 3 to 12.

Figure 8. Representative frequency variation of the nf_H resonances with height corresponding to the Alouette II data of the present investigation.

Figure 9. Comparison between an Alouette II ionogram recorded when the low power transmitter was in operation (top) and one recorded when the high power transmitter was in operation (bottom); f_{Q2} and f_{Q3} are the electrostatic wave resonances [Warren and Hagg, 1968]. The top ionogram is one of the four ionograms corresponding to the data points enclosed by solid lines in Figs. 7a and 7b; both ionograms are from the 2000 km data sample (top: QUI pass 6110, 28 April 1967, 12:28:04 UT, -5° latitude, 62° west longitude, 1960 km; bottom: LIM pass 8194, 21 October 1967, 04:36:57 UT, -8° latitude, 79° west longitude, 2019 km).

Figure 10. Resonant duration vs. f_N/f_H for the f_H, $2f_H$, and $3f_H$ resonances as observed on 4 Alouette II satellite passes. The variation of f_H, H, and cos β corresponding to each pass is presented in the bottom row. The cut-off of the $3f_H$ data points near f_N/f_H = 1 is an instrumental effect since only resonances observed in the frequency range below 2.0 MHz are plotted.

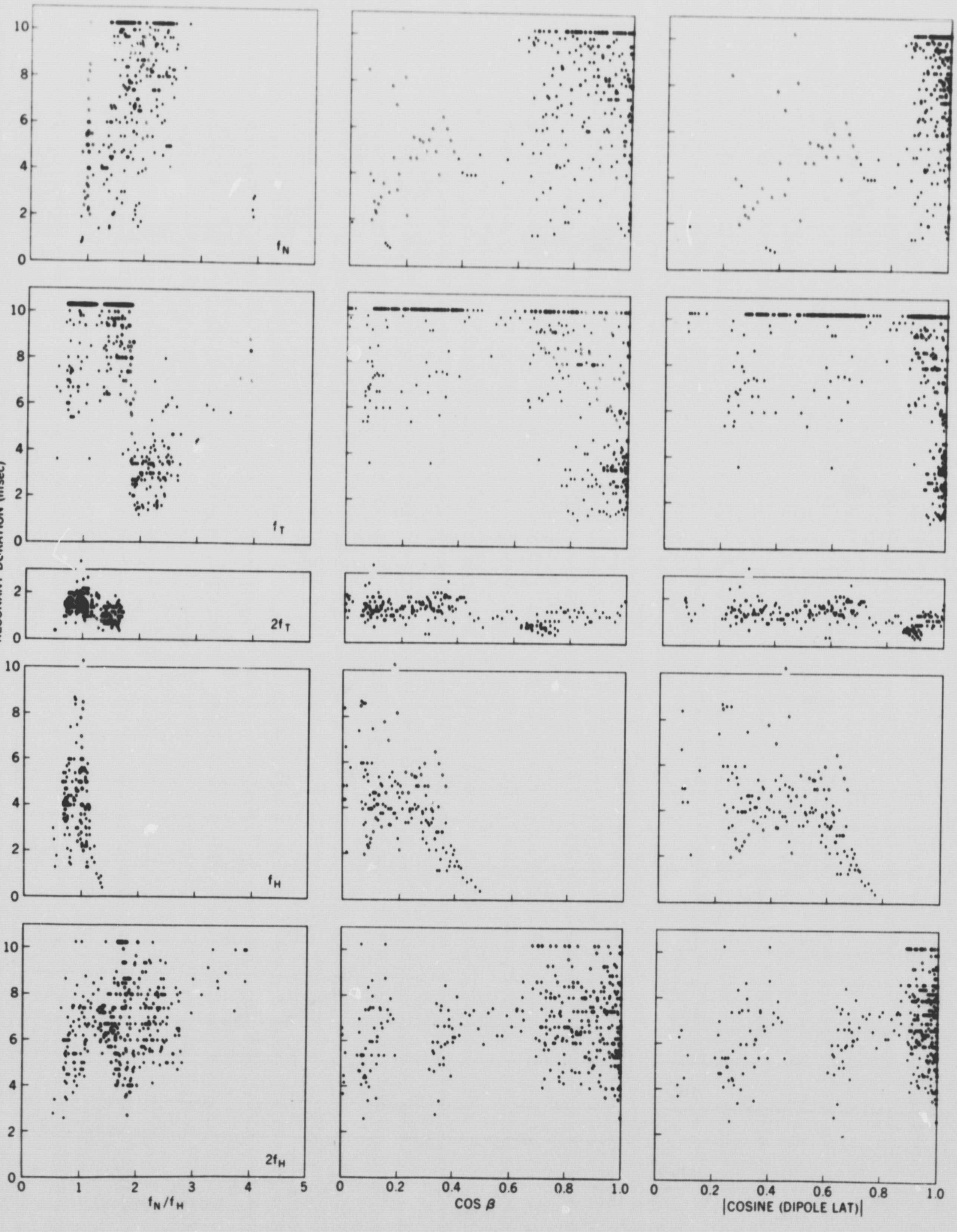

RESONANT DURATION (msec)
f_N
f_T
$2f_T$
f_H
$2f_H$
f_N/f_H
COS β
|COSINE (DIPOLE LAT)|

Figure 1a

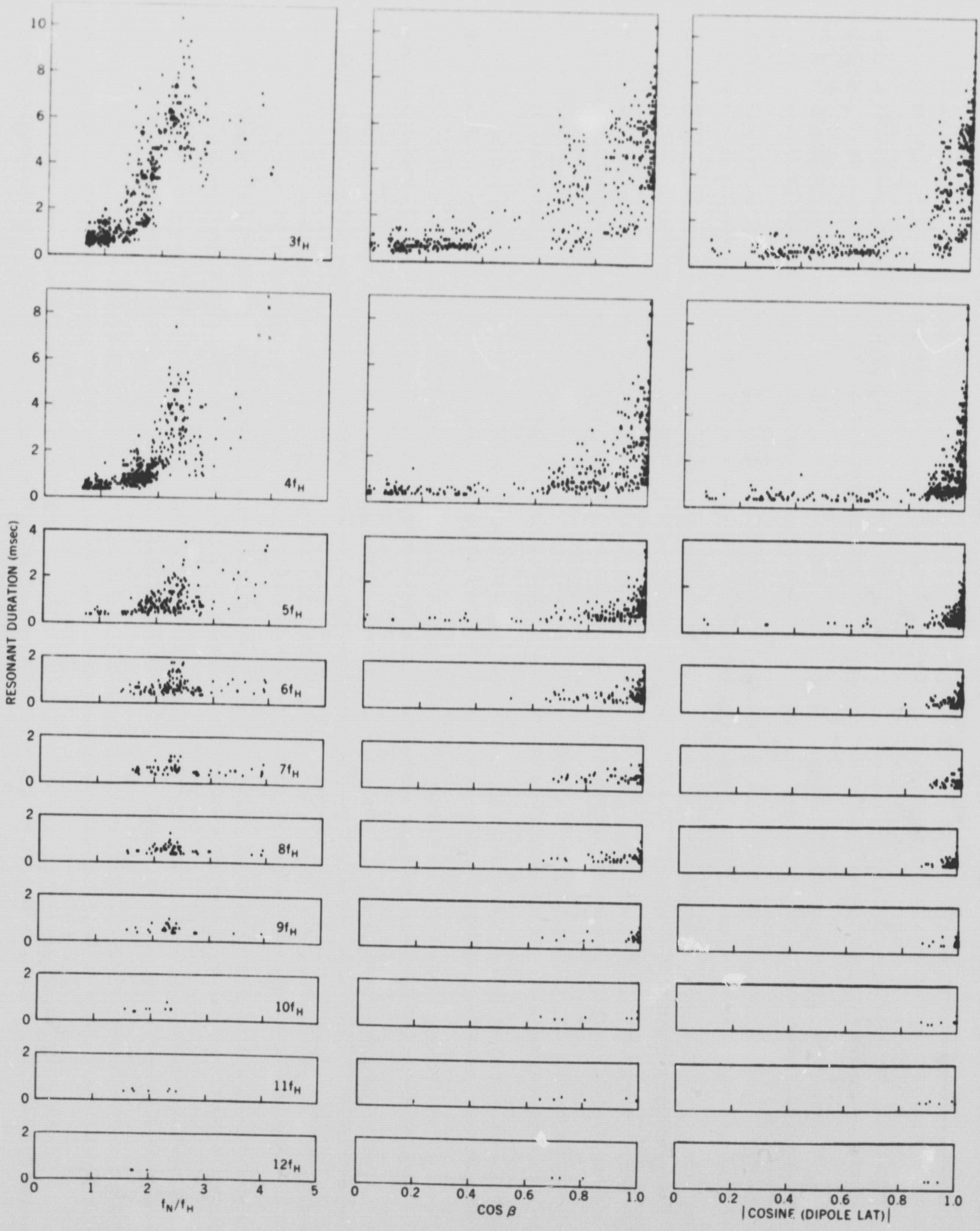
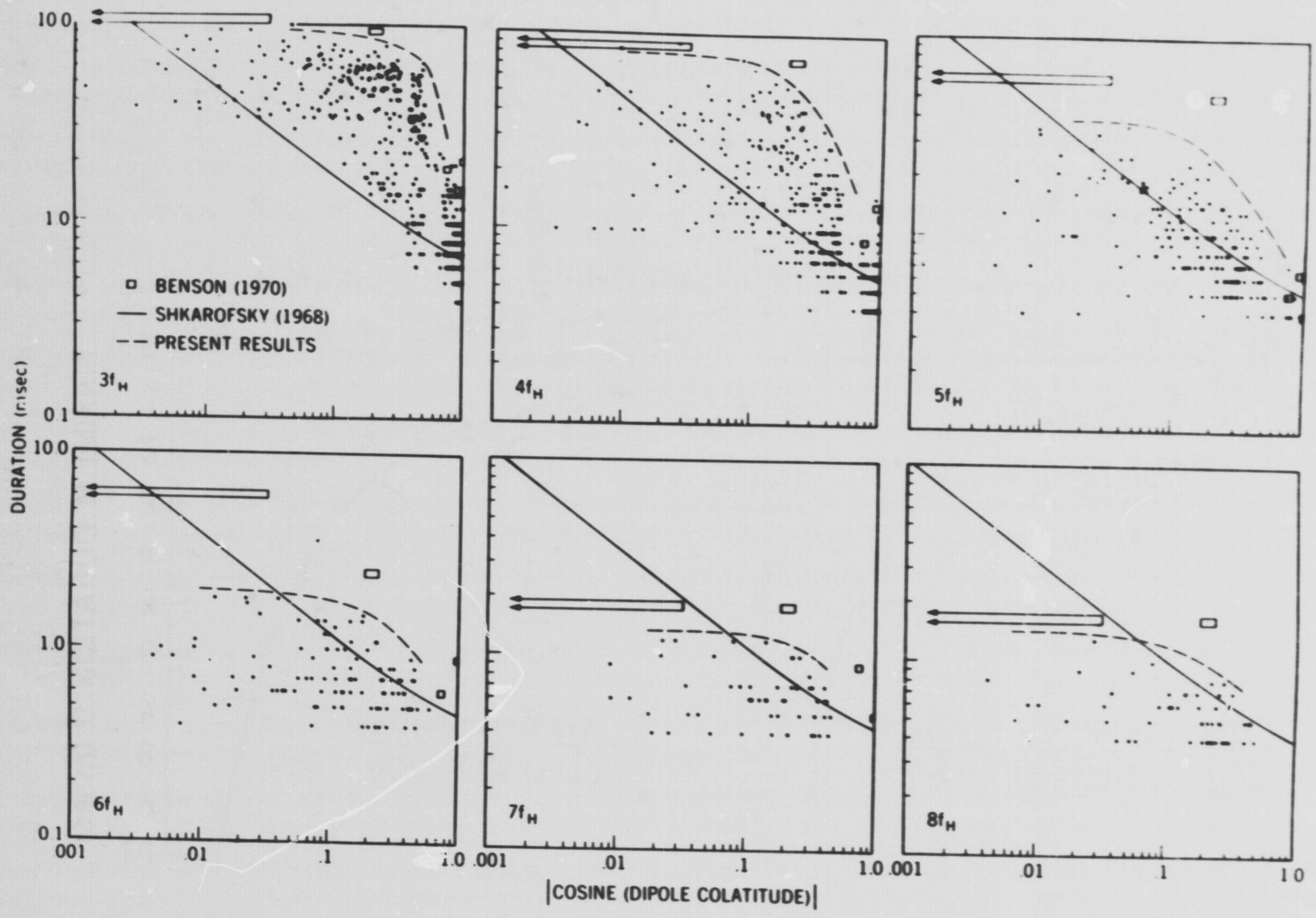

RESONANT DURATION (msec)
3f_H
4f_H
5f_H
6f_H
7f_H
8f_H
9f_H
10f_H
11f_H
12f_H
f_N/f_H
COS β
|COSINE (DIPOLE LAT)|

Figure 1b



BENSON (1970)
SHKAROFSKY (1968)
PRESENT RESULTS
DURATION (msec)
|COSINE (DIPOLE COLATITUDE)|
3f_H
4f_H
5f_H
6f_H
7f_H
8f_H

Figure 2

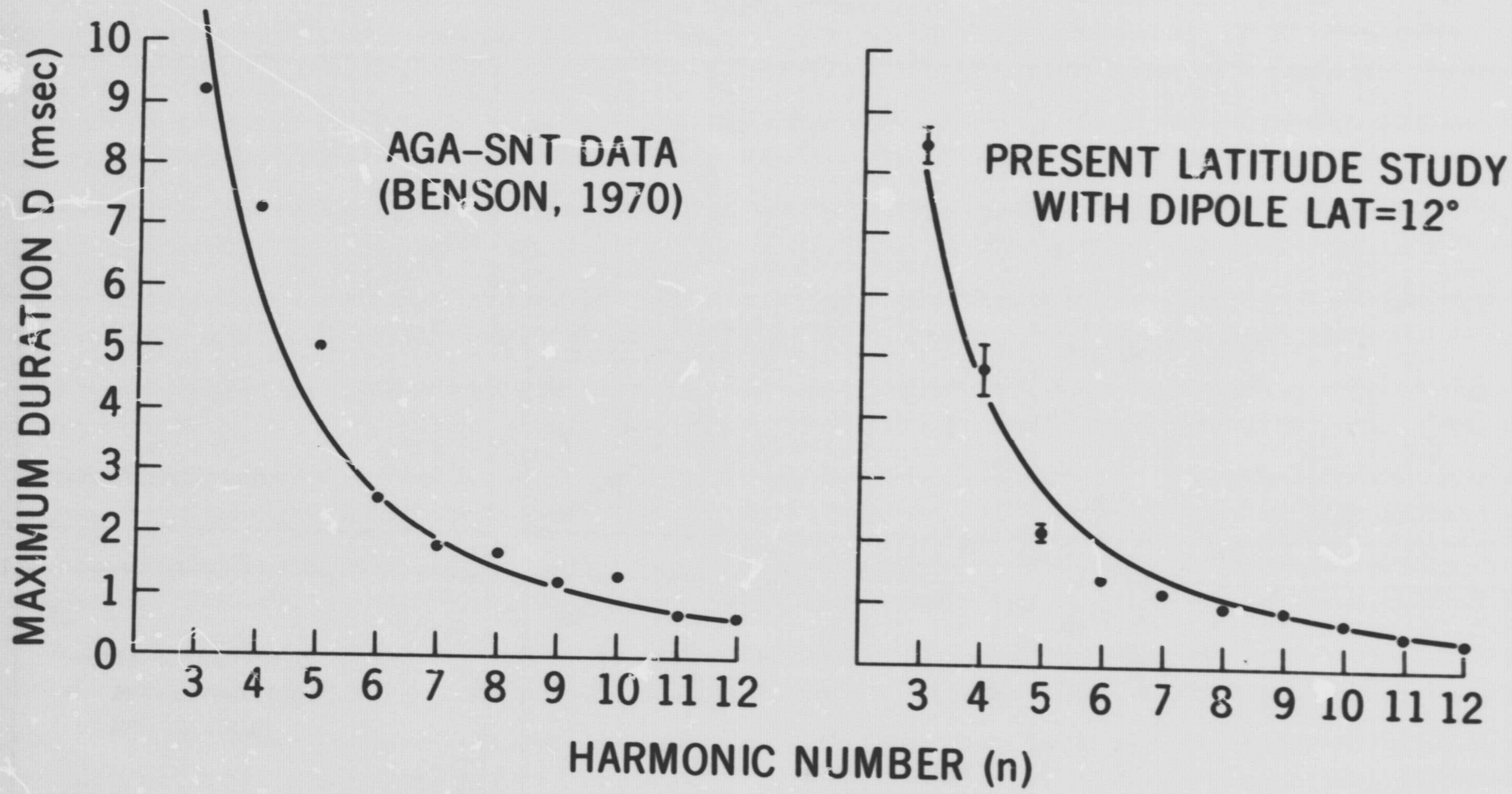

MAXIMUM DURATION D (msec)
10
9
8
7
6
5
4
3
2
1
0
AGA-SNT DATA
(BENSON, 1970)
PRESENT LATITUDE STUDY
WITH DIPOLE LAT=12°
3 4 5 6 7 8 9 10 11 12
3 4 5 6 7 8 9 10 11 12
HARMONIC NUMBER (n)

Figure 3

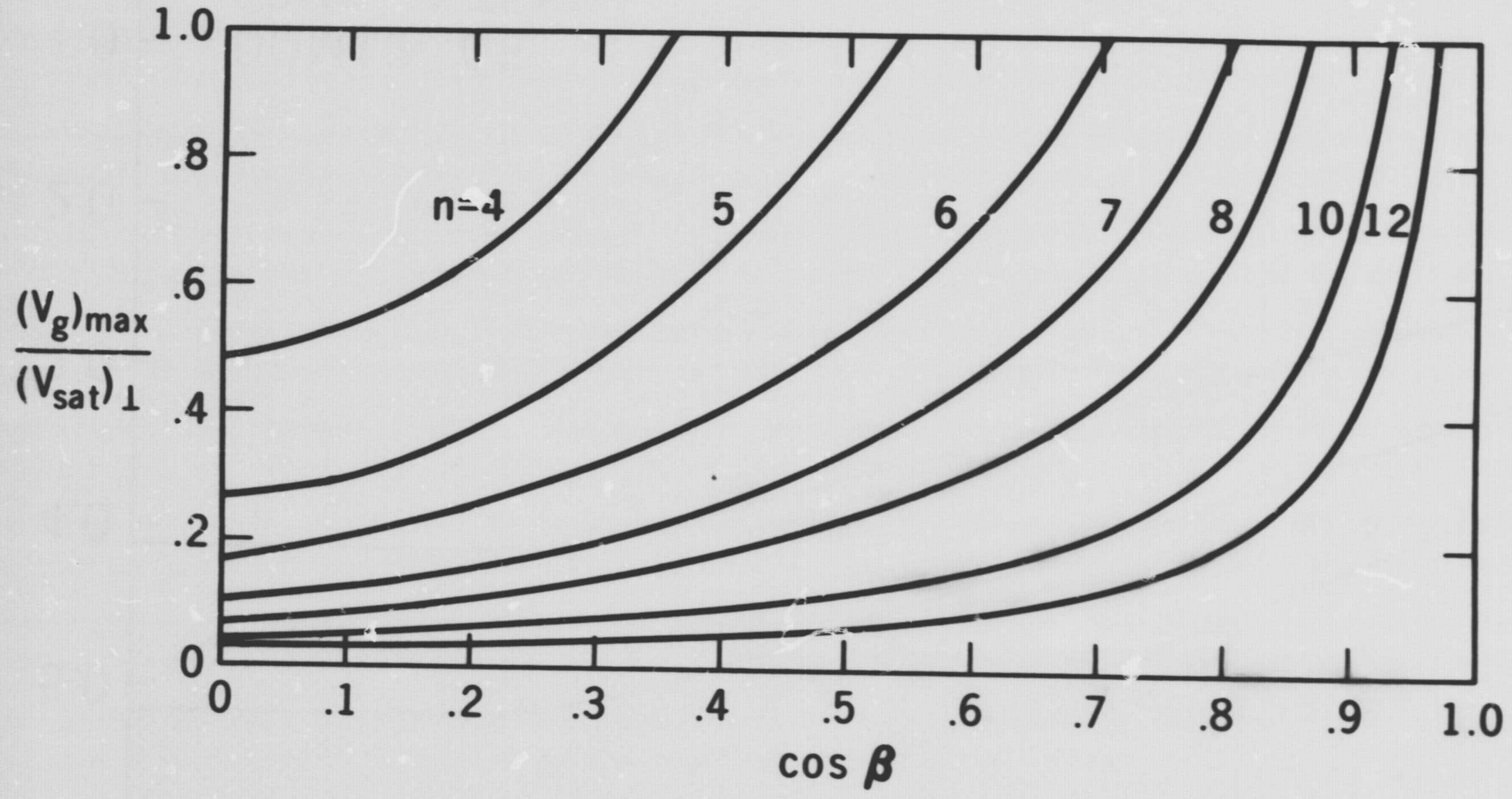


Figure 4

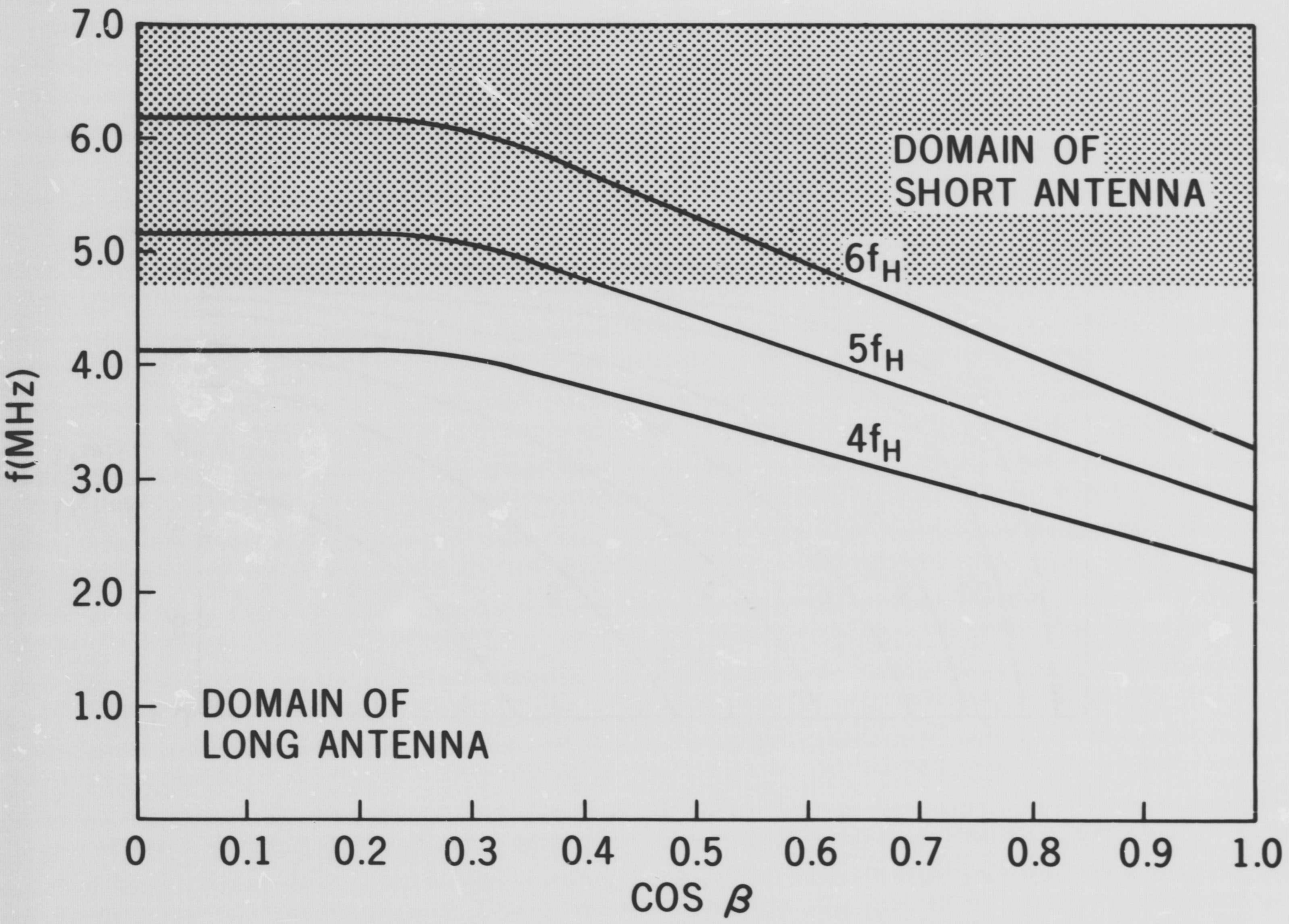
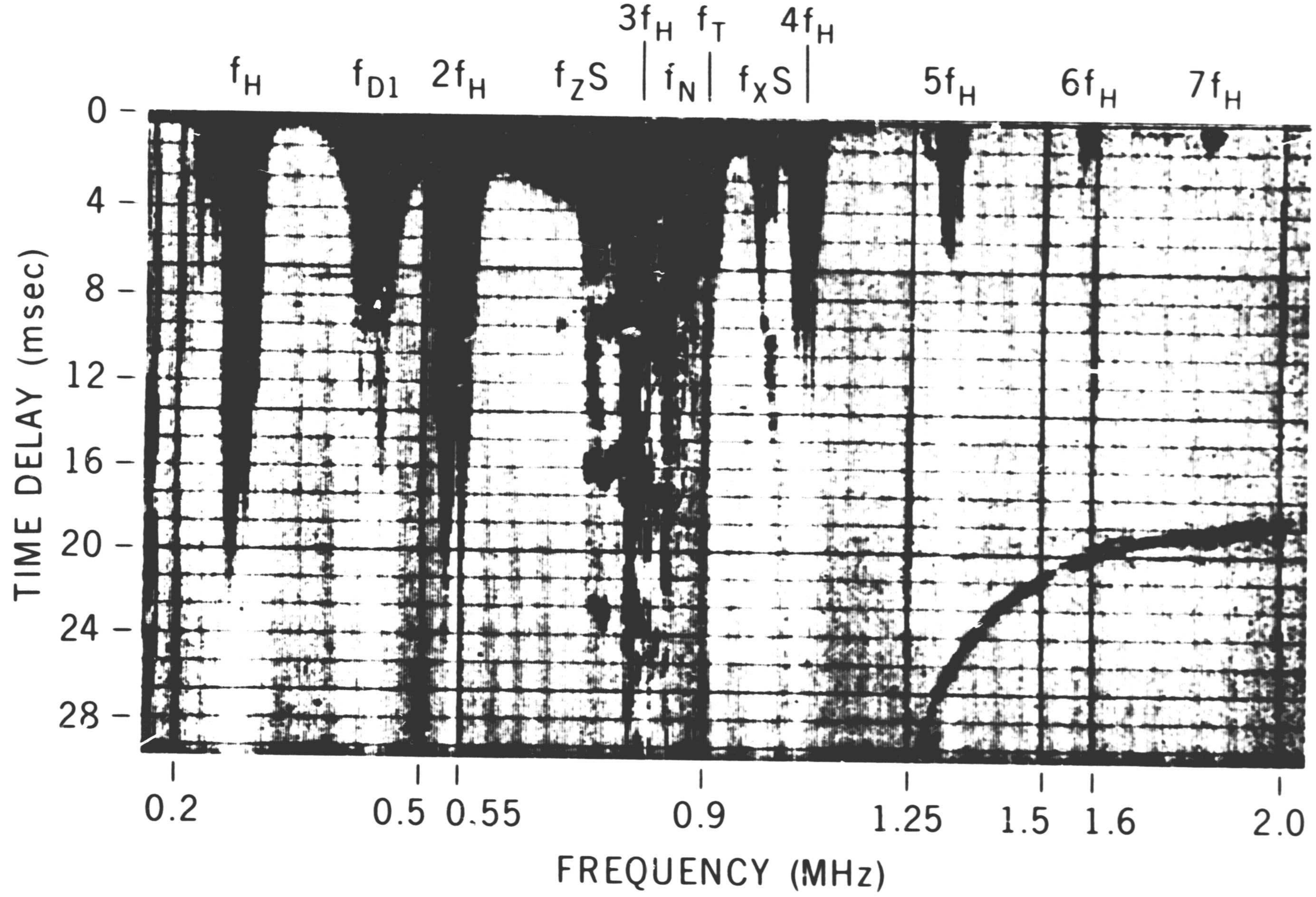

7.0
6.0
5.0
4.0
3.0
2.0
1.0
f(MHz)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
COS β
DOMAIN OF
SHORT ANTENNA
DOMAIN OF
LONG ANTENNA
6fH
5fH
4fH

Figure 5



f_H
f_{D1}
$2f_H$
f_ZS
$3f_H$
f_N
f_T
f_XS
$4f_H$
$5f_H$
$6f_H$
$7f_H$
TIME DELAY (msec)
0
4
8
12
16
20
24
28
0.2
0.5
0.55
0.9
1.25
1.5
1.6
2.0
FREQUENCY (MHz)

Figure 6a

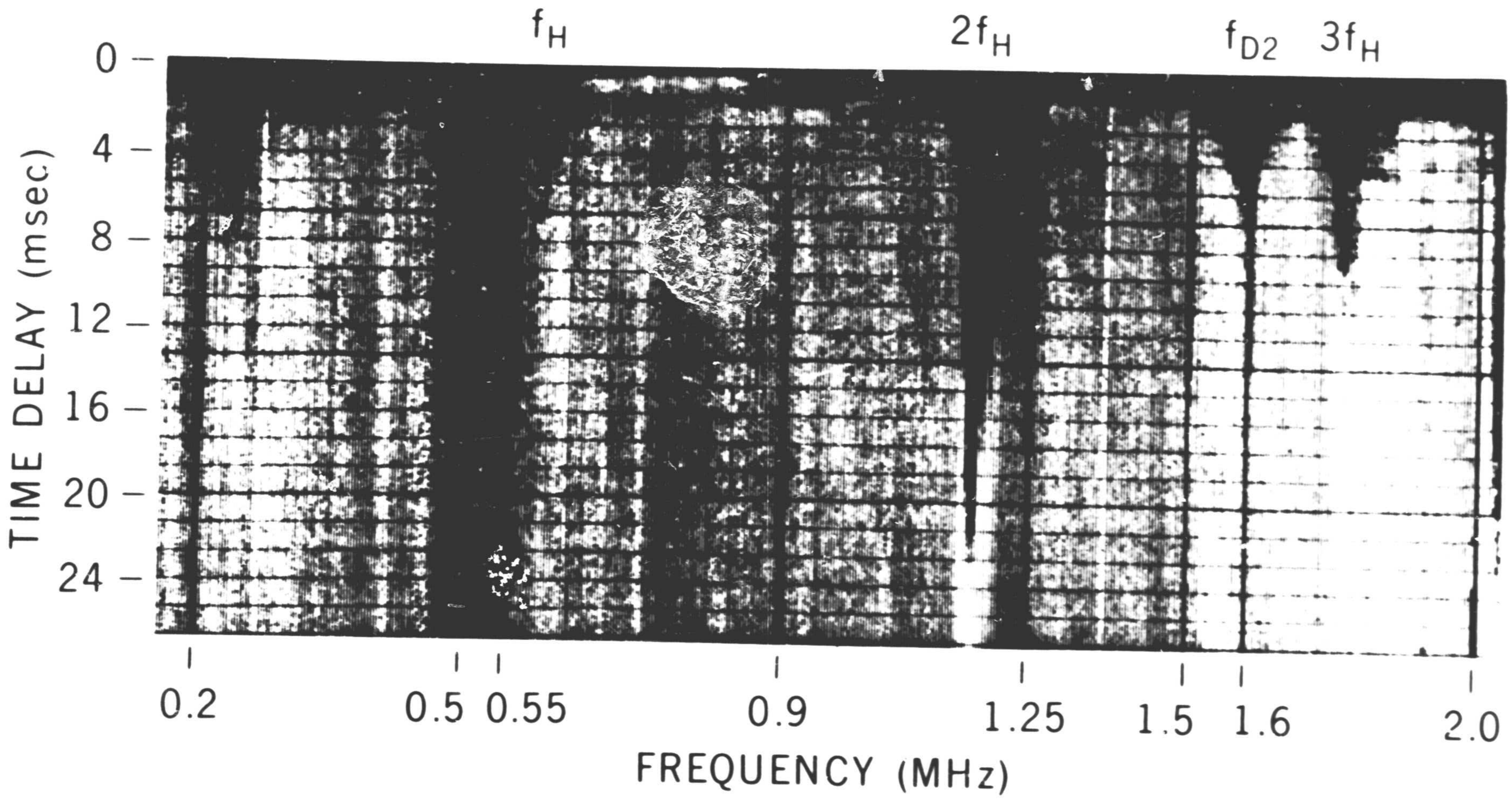

f_H
2f_H
f_D2
3f_H
TIME DELAY (msec)
0
4
8
12
16
20
24
0.2
0.5
0.55
0.9
1.25
1.5
1.6
2.0
FREQUENCY (MHz)

Figure 6b

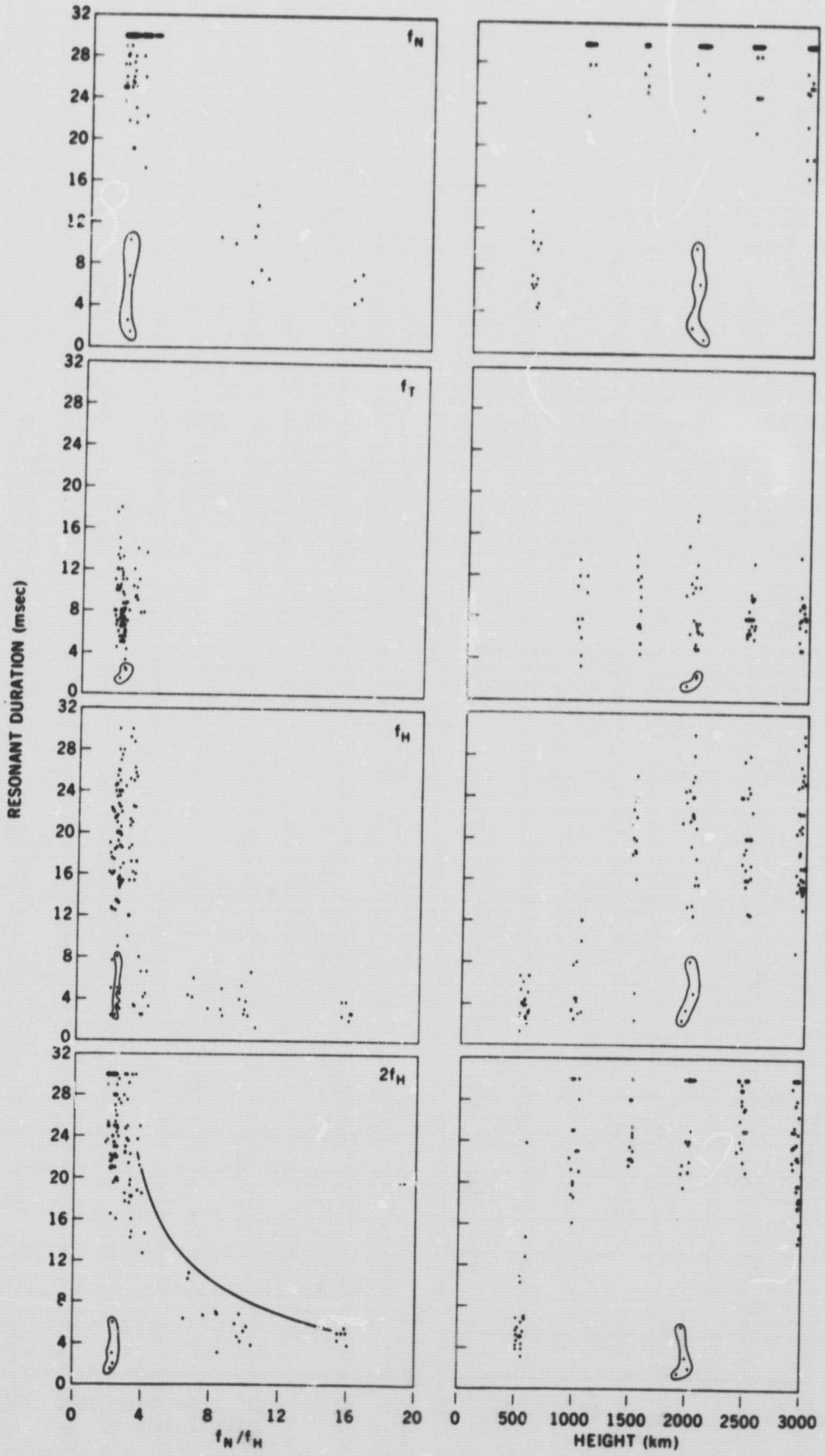


Figure 7a

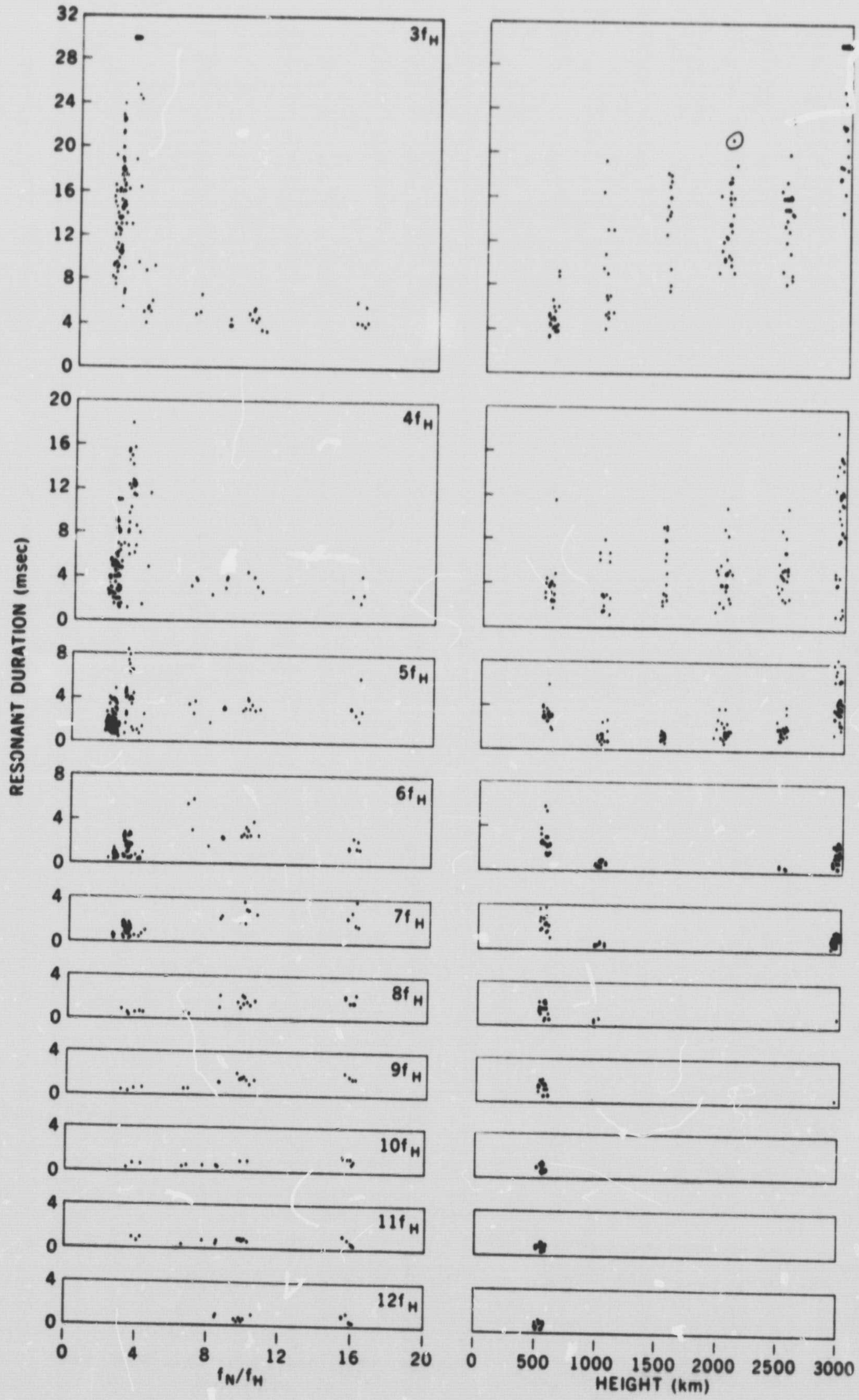

RESONANT DURATION (msec)
3f_H
4f_H
5f_H
6f_H
7f_H
8f_H
9f_H
10f_H
11f_H
12f_H
0 4 8 12 16 20
f_N/f_H
0 500 1000 1500 2000 2500 3000
HEIGHT (km)

Figure 7b

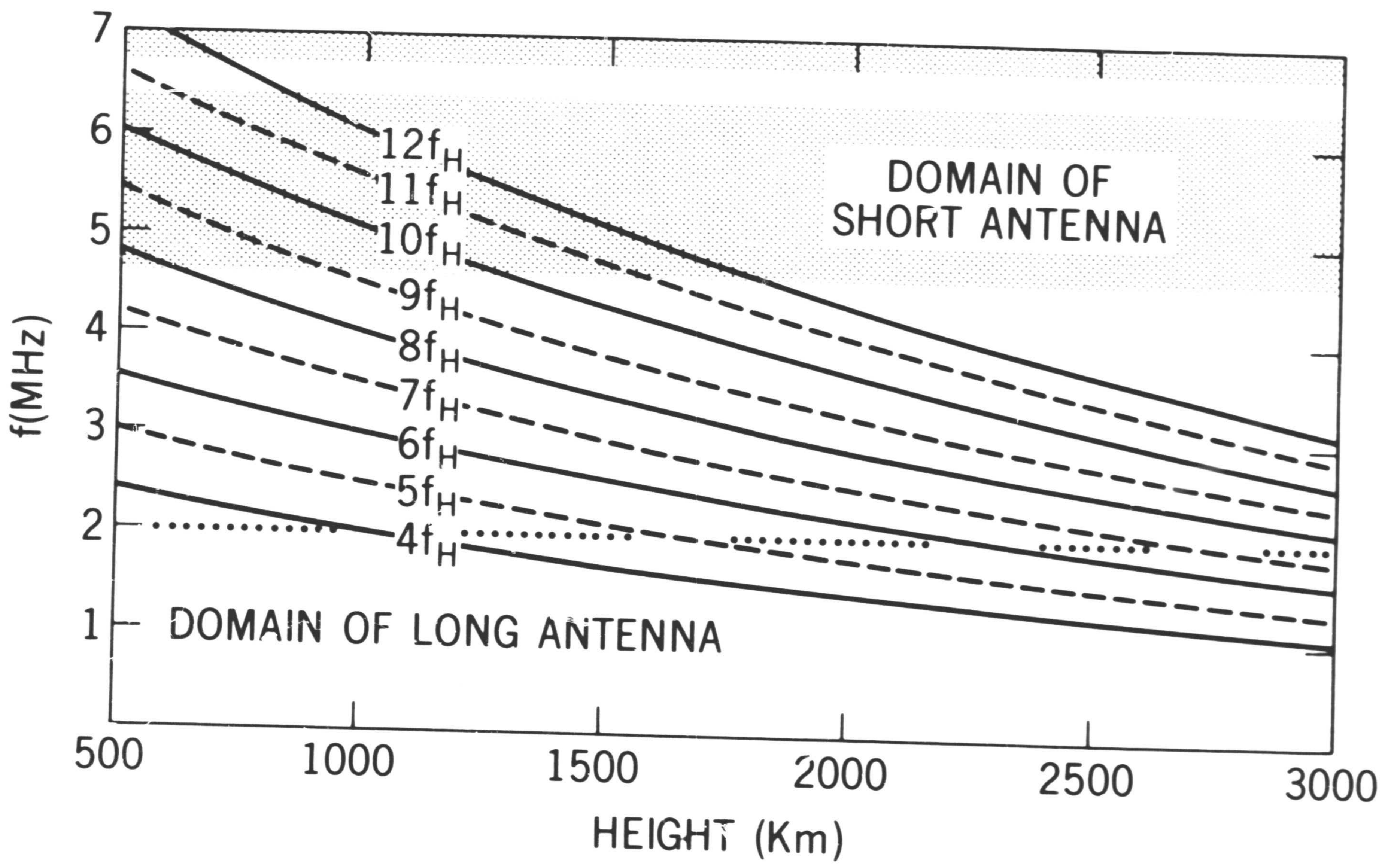

DOMAIN OF
SHORT ANTENNA
DOMAIN OF LONG ANTENNA
12f$_H$
11f$_H$
10f$_H$
9f$_H$
8f$_H$
7f$_H$
6f$_H$
5f$_H$
4f$_H$
f(MHz)
7
6
5
4
3
2
1
500
1000
1500
2000
2500
3000
HEIGHT (Km)

Figure 8

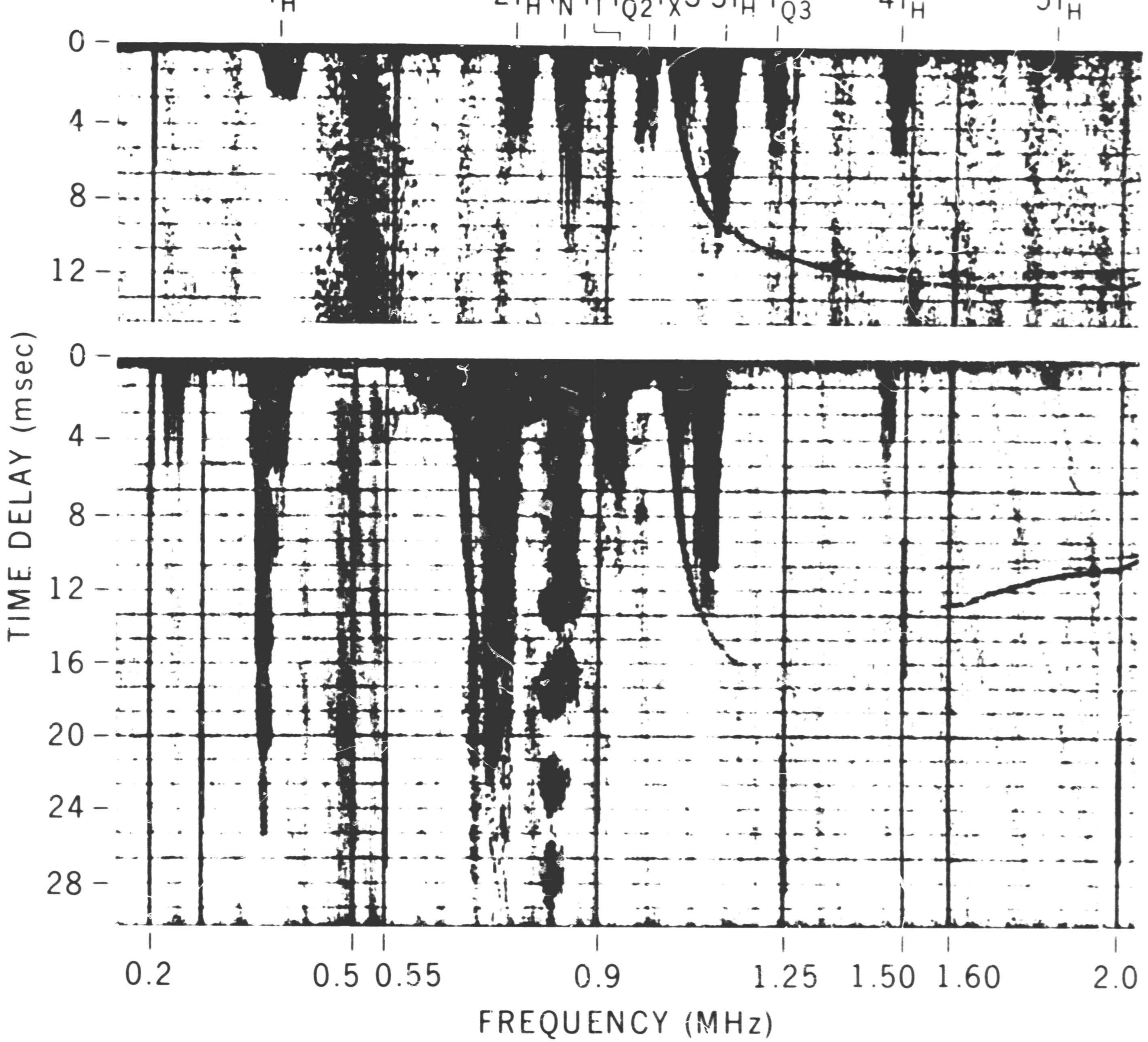

TIME DELAY (msec)
0
4
8
12
0
4
8
12
16
20
24
28
0.2
0.5 0.55
0.9
1.25
1.50
1.60
2.0
FREQUENCY (MHz)

Figure 9

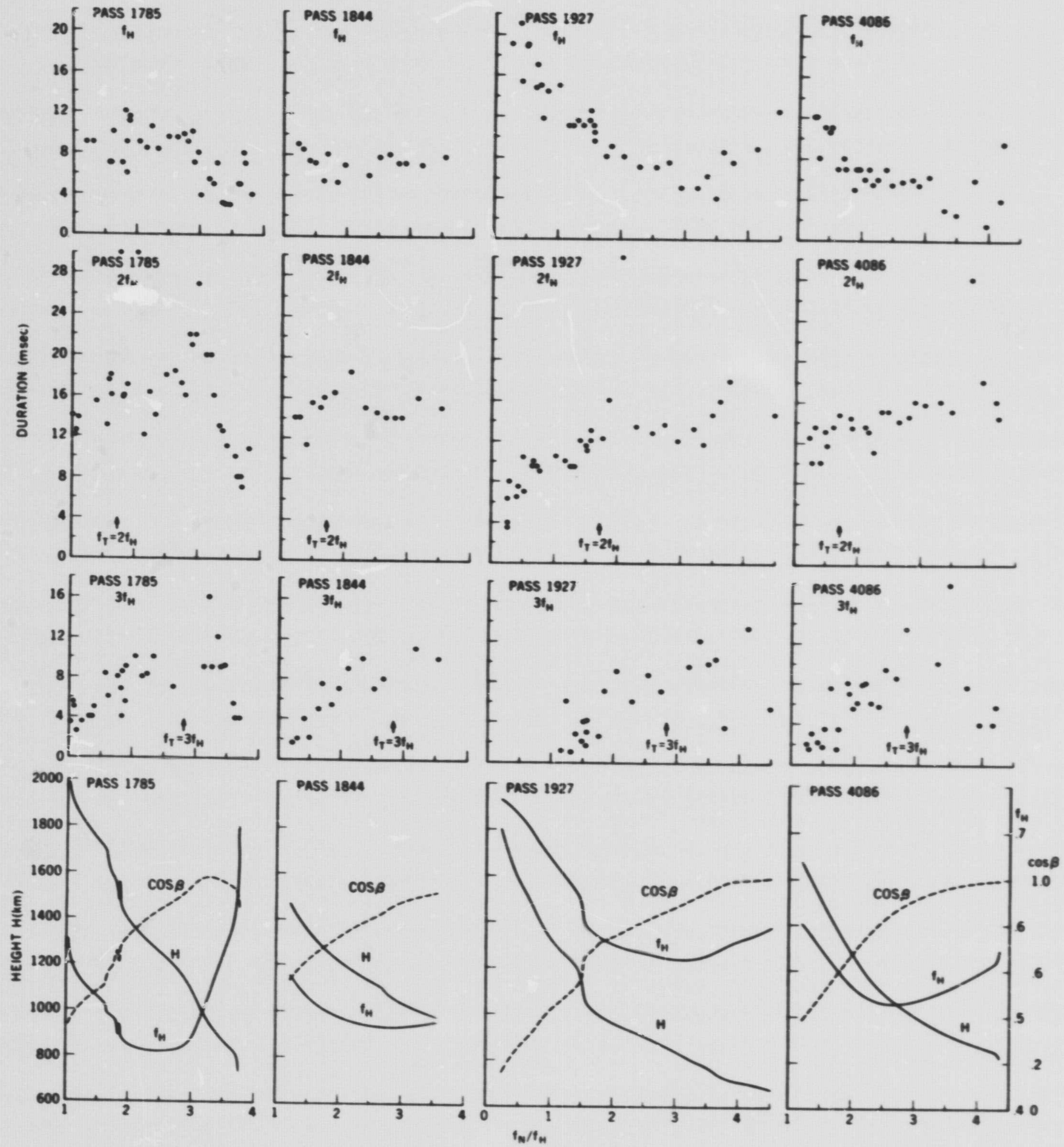

PASS 1785
PASS 1844
PASS 1927
PASS 4086
DURATION (msec)
HEIGHT H(km)
COSβ
H
f_H
$f_T = 2f_H$
$f_T = 3f_H$
f_N/f_H
cosβ

Figure 10